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CHANGES IN SOME PHYSICAL PROPERTIES OF ACTIVATED SLUDGE UNDER DIFFERENT BIOLOGICAL CONDITIONS

By

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CHANGES IN SOME PHYSICAL PROPERTIES OF ACTIVATED SLUDGE UNDER DIFFERENT BIOLOGICAL LOADING CONDITIONS

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Abstract

CHANGES IN SOME PHYSICAL PROPERTIES OF ACTIVATED SLUDGE UNDER DIFFERENT BIOLOGICAL LOADING CONDITIONS

It is felt that the present parameter (SVI) used for measuring settleability of activated sludge is insensitive to changes in activated sludge due to various biological conditions often encountered in treatment plant operation. A study of rheological properties of activated sludge showed that, unlike viscous fluid, activated sludge exhibits a yield strength even in dilute concentration. Presence of this yield strength is a unique property in activated sludge and it is believed that yield strength is directly related to the force affecting the settling of an activated sludge suspension. There are evidences in the literature that the settling rate of activated sludge is dependent upon the biological loading to which a system is subjected.

In an attempt to find out a suitable parameter for measuring physical properties of sludge under different organic loading conditions, a viscometer was developed for measuring the rheological properties of activated sludge. It was found that physical parameters like yield strength and plastic viscosity could be used to detect changes in activated sludge due to different biological conditions and might be used for control of treatment plant operations.

It is suggested that further studies should be made with various types of wastes before arriving at a definite relationship between physical properties and settleability of sludge under different organic loading conditions. It is also felt that these parameters might be suitably used to detect biological changes in activated sludge under different deficient nutrient conditions.

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1. INTRODUCTION

In aerobic treatment processes, much of the colloidal and dissolved organic materials are converted to a microbial suspension which is subsequently removed by gravity settling. In order to achieve good performance of the activated sludge process, much attention is often given to separation of suspended biological mass by gravity settling so that harmful organic matters are not carried over with the treated effluent from the plant. Also, maintaining a concentrated underflow of mixed liquor suspended solids for return to the aeration tank is important.

Satisfactory removal of biological suspended material from the effluent from a treatment plant requires a thorough understanding of basic characteristics of the microbial populations and their behavior under different biological and physical conditions. The activated sludge process is a biological treatment method for organic wastes and is characterized by two phenomena, namely, synthesis of cellular material resulting in new cells and respiration by the cells. Energy in the form of organic waste is required for both the above metabolic processes. Microorganisms may show good settleability or remain dispersed in suspension depending upon their energy levels. McKinney (1962) showed that usually a microbial population in high energy level tends to remain dispersed whereas in lower energy level it may show good settleability. Physical factors like viscosity, bouyancy and the structure of the suspension, on the other hand, are important in physical settling of suspended organisms. The design criteria for any biological waste treatment method are often obtained by considering the above biological and physical factors. One of the biological factors is the amount of energy available in the form of

organic substrate to the microorganisms per unit weight of biological sludge or per unit volume of suspension.

In laboratory evaluations of the design criteria, the biological factors like energy levels, growth rate, etc. are often determined by using pure cultures and simple organic matters, whereas the physical parameters are usually evaluated from the study of inert organic and inorganic substances in suspension. However, the information obtained from these studies may be far from that observed in actual treatment operations of domestic or industrial wastes due to the complex nature of wastes and heterogeneity of the biological population, and may not be quantitatively applicable to the actual treatment process. But they contribute to the fundamental knowledge about the mechanisms involved in the treatment processes.

1.1 Purpose of the Study

The primary objective of this study was to observe the physical changes in a microbial suspension under different biological conditions. An attempt was made to study the physical and biological properties of the suspension in an environmental condition similar to an actual conventional treatment plant. The organic loading (commonly expressed in pounds of biological oxygen demand (BOD) per pound of microorganisms), was used as the biological parameter. The changes in physical properties due to different organic loading conditions were measured in terms of the yield strength and plastic viscosity of the suspension. Unfiltered settled waste from the local Champaign-Urbana Sanitary District plant was used as organic feed in the experiments. The sewage sample collected from the treatment plant varied considerably in characteristics. The microorganisms from the

aeration chamber of the activated sludge treatment unit were used as the initial seed material in the laboratory units. The yield strength and viscosity were measured with a coaxial cylinder rotational viscometer especially designed for the study.

2. LITERATURE REVIEW AND THEORETICAL CONSIDERATIONS

A number of studies have been conducted to establish the effect of biological loadings on the settling characteristics of activated sludge. In these studies the loading parameter has been calculated from the food-to-microorganism ratio. The measurement of the sludge volume index (SVI) has long been used as a tool to indicate the quality of activated sludge and to control the treatment process so far as settling properties of sludge are concerned. Efficient control of such a process requires early detection of any variation from normal performance, but sludge volume index is not sensitive enough to the changes in sludge quality. So it is felt that introduction of some measurable physical parameters like yield strength or plastic viscosity which are directly connected with the biological and physical changes in settling sludge would be helpful in working out a basis for design of the activated sludge treatment processes.

Logan and Budd (1955) showed that the sludge volume index was related to the biological loadings (expressed as pounds of BOD per pound of sludge). High sludge volume indices which are associated with poorly settling sludge occurred with very low organic loadings as well as very high organic loadings. They explained that under high loading conditions the accumulation of unoxidized organic matter occurred in the sludge and in the case of low loadings the competition among microorganisms for scarce food supply resulted in the establishment of new flora and fauna. Ford and Eckenfelder (1966) studied different process variables in the activated sludge process and obtained a similar relationship between sludge volume index and biological loadings. The settleability was reduced at

both ends of the load spectrum, but the reduction was more significant at higher organic loadings. They explained that poor settleability at low loadings was probably due to unoxidized fragments of flocs being broken up with a consequent reduction in specific gravity while poor settleability at higher loadings was due to the predominance of filamentous forms of organisms. They observed these organisms in abundance at organic loadings exceeding 0.7 lb BOD per lb of solids. They concluded that best sludge settleability could be obtained in an activated sludge process in the loading range of 0.2 to 0.7 lb BOD per lb of sludge.

Klegerman (1962) showed that in an activated sludge process the biological loading may vary over a wide range from an approximate low value of 0.05 in extended aeration process to 5.0 lb BOD per lb of sludge in a supra-activation process. But they did not study settling properties of the sludge at these extreme conditions. However, the conventional loading range was taken to be from 0.2 to 0.7 lb BOD per lb of sludge. The present study was conducted over the conventional loading range and loadings higher than this could not be obtained due to reasons discussed later.

The microbial population of the activated sludge is made up of bacteria, fungi, protozoa, rotifers and sometimes nematodes and other higher organisms. McKinney (1962) showed that generally the nature of organic compounds being stabilized determines which bacterial genera will predominate. A substrate with high protein content may favor Flavobacterium and Bacillus, whereas a high carbohydrate waste may tend towards Pseudomonas. Richards and Sawyer (1922) stated that high bacterial counts were associated with poor sludge settling whereas a populous protozoan sludge correlated with rapid settling of flocs.

In measuring poor settleability of activated sludge by sludge volume index a bulking sludge is often defined as a sludge which has a sludge volume index greater than 200 ml/gm. However, there are several opinions expressed in explaining the cause of sludge bulking. Jones (1966) observed that sludge bulking results in an emergence of a dominant population of filamentous microorganisms growing as a dispersed floc. He isolated some of them as Sphaerotilus natans and also Geotrichum candidum, an obligate aerobe. Pipes (1967) observed, "almost any disturbance in an activated sludge is manifested by loss of sludge in the effluent from the process. Unfortunately far too many of the personnel in the waste water treatment field refer to any loss of solids from an activated process as bulking...." He described sludge bulking either as nonfilamentous or filamentous. Nonfilamentous bulking was due to the physical nature of the sludge. Heukelekian and Weisberg (1956) showed that an increase in bound water content of the sludge produces a perceptible change in specific gravity of the sludge. Sludge organisms in a bulking sludge secrete an extracellular material with a high degree of hydration producing a sludge with excessive amounts of bound water and decreasing the specific gravity of the sludge. They explained that this reduction in specific gravity would increase the resistance of the sludge to settling and reduce the tendency to compact by squeezing out the loosely associated nonbound interstitial water. They concluded that a bulking sludge could be changed to a nonbulking one by changing the organic loading. Ford and Eckenfelder (1966) showed that an organic loading higher than 0.7 lb BOD per lb of mixed liquor suspended solids was associated with a predominance of filamentous organisms.

Activated sludge is physically comprised of nonrigid flocculent particles which aggregate into large floc, the sizes being subject to change depending on the local shear rate. Dick and Ewing (1967) showed that these aggregate particles even in dilute concentration form a structured suspension exhibiting a yield strength. A breakdown in the structure formed within the suspension could hasten the rate of settling. Mancini (1962) showed that stirring in the compression zone hastens the rate of fall of the interface between the zone of constant concentration and the clear liquor. Dick (1965) obtained a relationship between the rheological properties and settling properties of activated sludge. Starting with the basic concept of forces acting on a suspended particle he showed that the subsidence velocity is dependent on the depth of sludge mass, concentration and the magnitude of structural support force which he described as a force acting against the direction of settling due to the very nature of activated sludge. In absence of this force the settling velocity becomes a function of local concentration of particles only, which was the basic assumption of Kynch (1952) in his theory of sedimentation for an ideal suspension. Dick (1965) showed a mathematical expression for structural support force (F_s) as given by the expression

$$F_s = K_2 \frac{CDR}{SD + 2R} \tag{1}$$

where C = suspended solids concentration

D = depth of suspension

S = slope of D/V vs D curve

R = retardation factor

K_2 = constant of proportionality

V = settling velocity of sludge

It was shown that the structural support force (F_s) was a function of the retardation factor which again was connected with the concentration (C) of sludge in the following manner

$$R = ge^{hc} \tag{2}$$

where g and h are constants depending upon the biological condition of the sludge.

For a Newtonian fluid or a viscous fluid, the shearing stress (τ) is directly proportional to the rate of shear $\frac{dv}{dx}$ and is given by the expression

$$\tau = \mu \frac{dv}{dx} \tag{3}$$

where μ is the absolute viscosity of the fluid. Green (1949) determined the flow curves for pseudoplastic materials. These substances become increasingly less viscous with increased rate of shear and are given by

$$\tau = K \left(\frac{dv}{dx}\right)^n \tag{4}$$

where K is a constant of proportionality with the same dimension of viscosity and n is a dimensionless constant.

In plastic materials the solid phase of the suspension forms a continuous structure and until the yield strength is exceeded plastic materials behave like elastic materials. At high stress plastic materials flow viscously and the stress is given by the expression

$$\tau = \tau_y + \eta \frac{dv}{dx} \tag{5}$$

where τ_y is the yield strength of the material and η is the plastic viscosity.

Very little information is available in the literature on the rheology of activated sludge. Some work in this area indicates that activated sludge possesses thixotropic behavior. Thixotropy is a phenomenon in which shear stress is dependent on time. The work of Hatfield (1938) and Geinopolos and Katz (1964) could be mentioned in this connection. The necessity for development of a suitable viscometer for measuring rheological properties of activated sludge has been felt by many investigators for a long time. Dick (1965) worked with a modified Brookfield viscometer and found out that activated sludge was thixotropic and either plastic or pseudoplastic. However, he could measure the yield strength of activated sludge and found yield strength to vary with concentration (C) in the same way as was observed between concentration (C) and retardation factor (R). The relationship is given by the expression

$$Y_s = Je^{KC} \tag{6}$$

where Y_s = yield strength

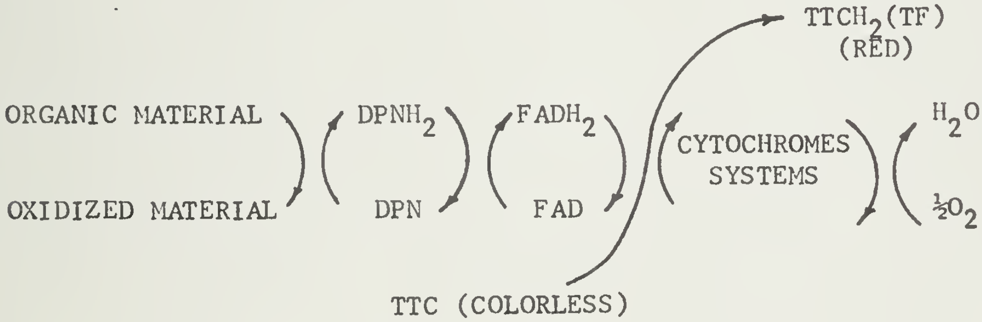
e = base of Naperian System of logarithms

J and K = constants depending on biological condition of sludge.

So, he concluded that yield strength and retardation factor might be governed by the same factors which influence the values of J and K and g and h as described before. Earlier Weltman and Green (1943) obtained similar relationships between yield strength and concentrations of different colloidal and pigment suspensions. Wang (1967) worked in this area and measured the yield strength of activated sludge with a suitable coaxial cylinder rotational viscometer. The same viscometer with slight modification was used in these studies with activated sludge as has been described in subsequent

chapters. The basic theories of rotational viscometry have been described by many and have been summarized by Dick and Ewing (1967) and are not discussed here.

The microbial populations in activated sludge perform their functions of oxidation and synthesis with the aid of enzymes. The sludge activity has been measured by various methods. Oxygen utilization rate has been accepted as a good indicator of sludge activity. In recent years the measurement of dehydrogenase enzyme activity has been used by many to evaluate sludge activity. Lenhard and Nourse (1964) introduced this measurement as a parameter of sludge activity. Ford _et al._ (1966) concluded that an excellent correlation of oxygen uptake and dehydrogenase activity did exist and described dehydrogenase measurement as a true indicator of sludge activity. In biochemical metabolic pathways organic compounds are broken down through a series of dehydrogenations. These enzymes can easily be measured by using a tetrazolium salt (triphenyl tetrazolium chloride or TTC) as the hydrogen acceptor. This couples the oxidation of the substrate to the reduction of colorless salt. The intensity of red color produced (triphenyl formazan or TF) is taken as a measure of dehydrogenase enzyme activity. The transfer mechanism is as follows:



3. MATERIALS AND METHODS

In order to measure physical properties of activated sludge in the laboratory, activated sludge was acclimated in laboratory treatment units with organic waste from the treatment plant.

3.1 Collection and Storage of Organic Wastes

Effluent from the primary settling tank at the Champaign-Urbana Sanitary District waste treatment plant was collected once a week in 18 ℓ containers and immediately stored in a constant temperature room below 5°C. This settled sewage was transferred to a reservoir inside a refrigerator, kept at a constant temperature of 4°C, from which it was pumped to continuous flow activated sludge units designed for this particular study. The domestic waste water in the treatment plant had a highly variable characteristic because the plant receives some intermittent discharge from local industries along with the sewage from the community. A summary of daily average values of suspended solid concentrations collected from the treatment plant on consecutive days are shown in Table 3.1.

3.2 Continuous Flow Activated Sludge Units

Laboratory units were made of plexiglass and consisted of a combination of aeration and settling compartments separated by a baffle wall with approximately 0.75 inch gap at the bottom. Four such units were operated simultaneously under different organic loadings. Air was supplied by aerators made of plexiglass tubing with perforations. The air supply was taken from laboratory wall connections by means of a distributor to divide the flow of air into four units. Continuous supply of waste water to the aeration units was maintained by positive displacement pumps* which

*Positive displacement pumps. Model No. A.L.4E, Sigma Motors, Inc., 3 N. Main St., Middleport, New York.

Total Suspended Solids (mg/ℓ)	Volatile Suspended Solids (mg/ℓ)	(percent)
128	111	86
285	248	87
142	130	91
119	106	89
169	148	87
196	173	88
157	134	85

Table 3.1 AVERAGE VARIATIONS IN SUSPENDED SOLIDS IN SEWAGE AS COLLECTED FROM CHAMPAIGN-URBANA WASTE TREATMENT PLANT DURING 7 CONSECUTIVE DAYS

were capable of maintaining a constant pumping rate of 1 to 25 ℓ per day. The arrangement of the setup is shown in Figure 3.1.

In order to maintain a uniform distribution of solids in the reservoir inside the refrigerator, the contents were stirred continuously by a magnetic stirrer.

Activated sludge from the aeration chamber of the local treatment plant was used as the initial seed for the units.

3.3 Acclimation Procedure

The laboratory units were kept at a constant volume of 2 ℓ including the settling compartment. The units were acclimated to different organic loadings by controlling the feeding rate. Approximately two days were required for acclimation. The sludges were considered to be acclimated when the chemical oxygen demand (COD) removal rate became constant. Acclimation curves at two different loadings (.08 and 0.12 lb BOD/lb MLSS) are shown in Figure 3.2.

A COD and 5-day BOD correlation was obtained from the values determined in the laboratory and the plot is shown in Figure 3.3. The BOD values were also checked with the values obtained in the treatment plant laboratory for the particular days of collection of samples. In subsequent tests COD values were determined and converted to BOD values for calculating organic loadings. Organic loadings were determined from the mixed liquor suspended solids concentration in the aeration chamber and BOD values.

3.4 Viscometer for Measuring Physical Properties of Activated Sludge

The viscometer consisted of coaxial vertical cylinders with an annular space in between them. The annular space was designed to be

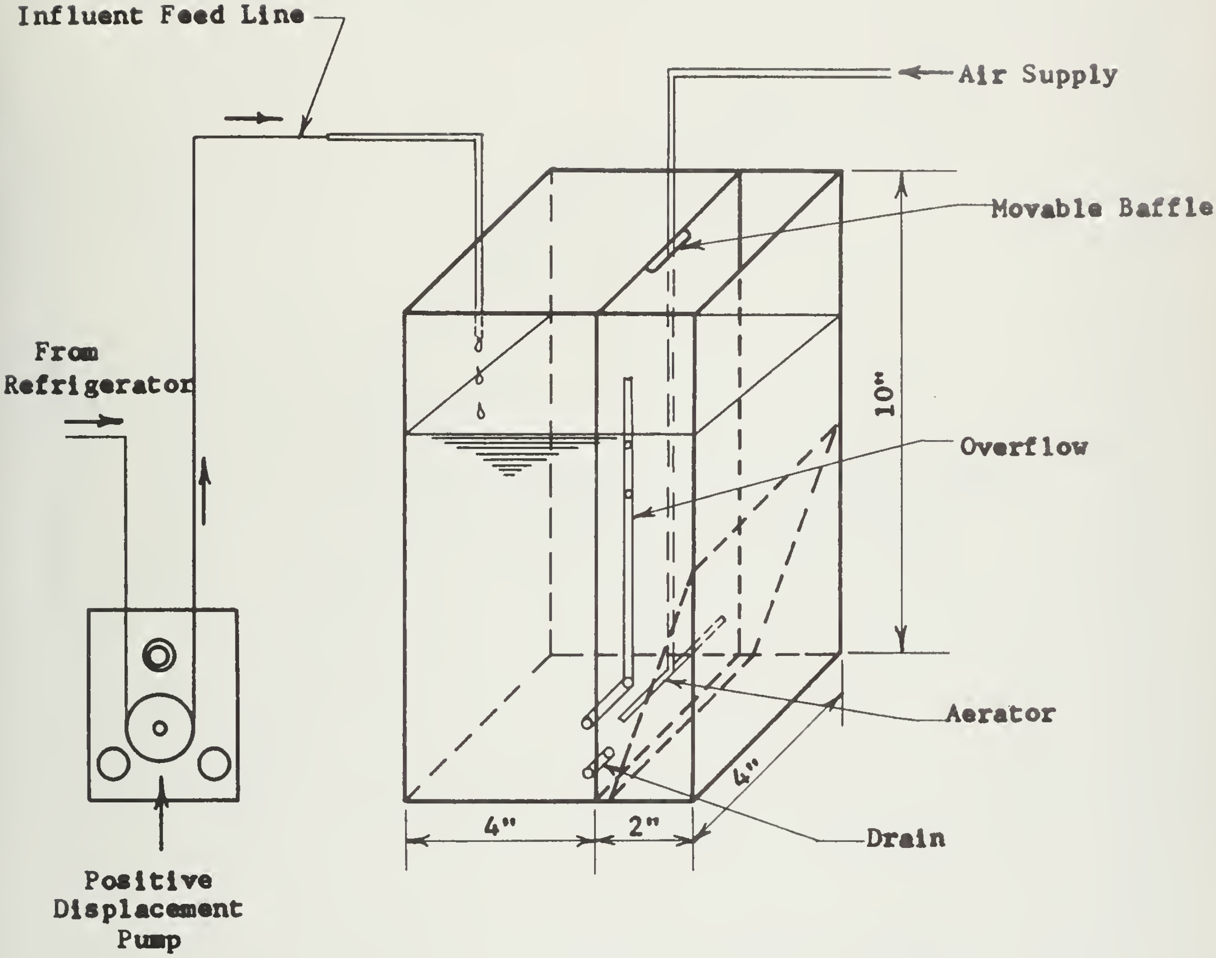


FIGURE 3.1 SCHEMATIC DIAGRAM OF CONTINUOUS FLOW ACTIVATED SLUDGE UNIT

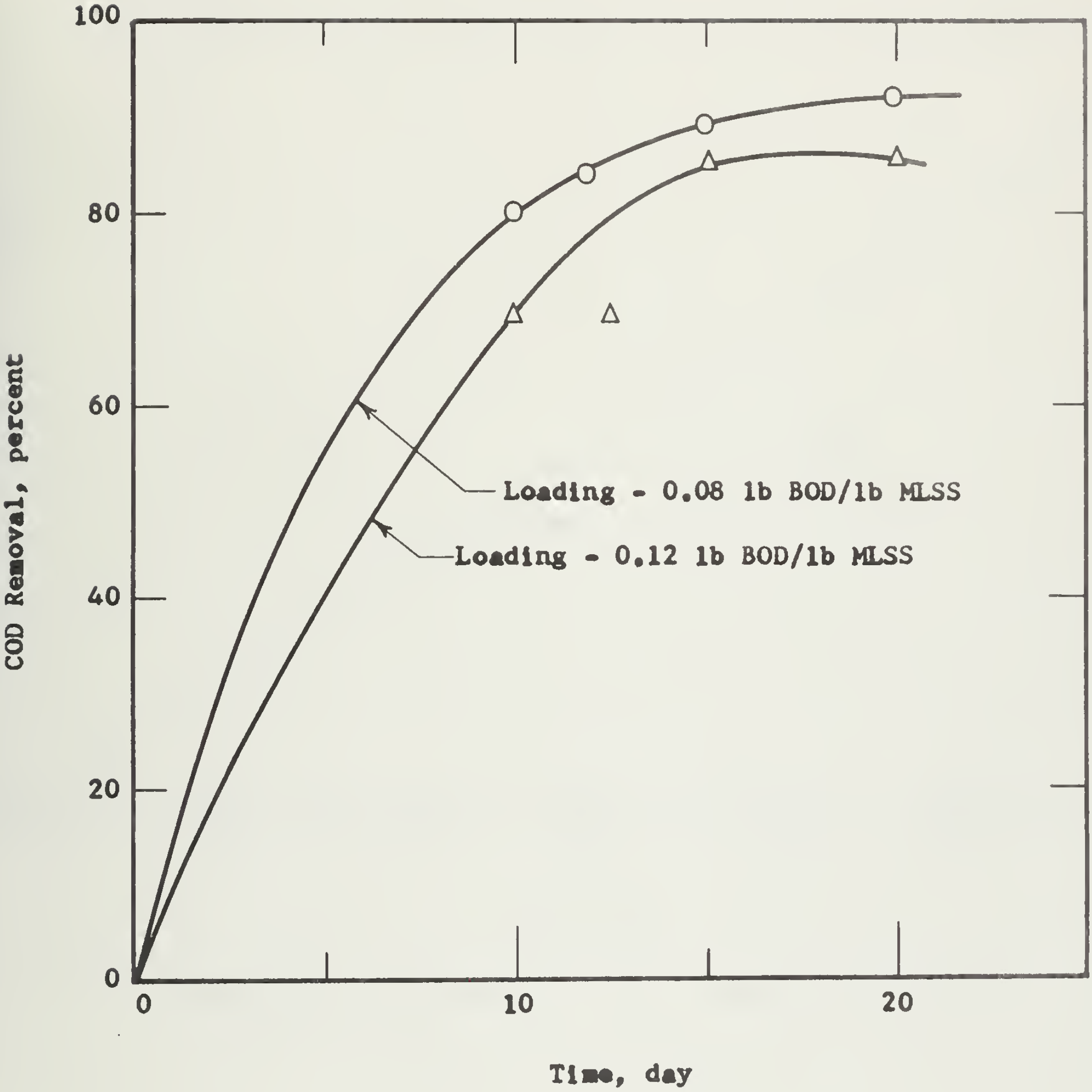


FIGURE 3.2 ACCLIMATION CURVES IN CONTINUOUS FLOW UNITS

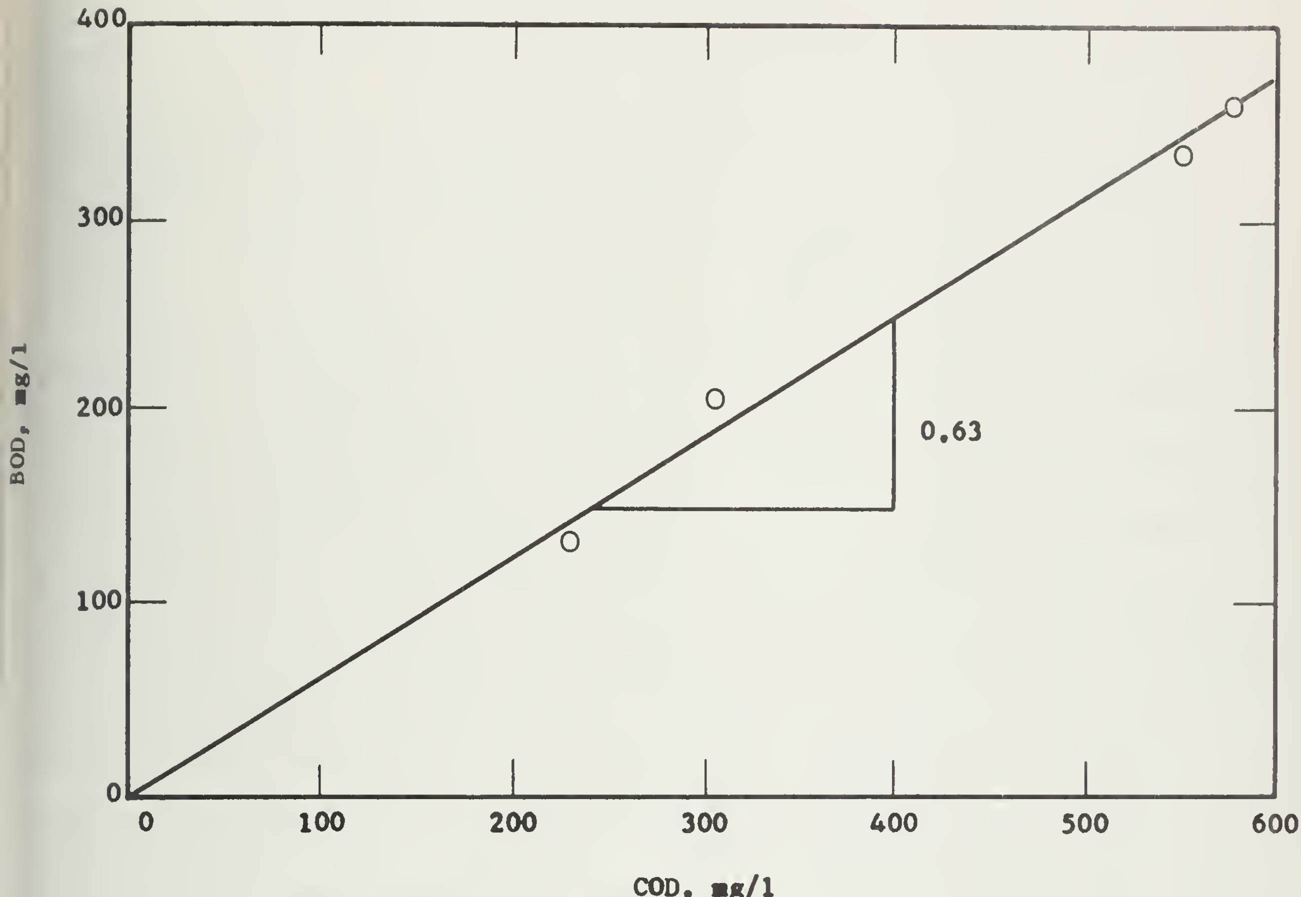


FIGURE 3.3 RELATIONSHIP BETWEEN BOD AND COD VALUES

occupied by the test fluid and the outer cylinder rotated. Dick's experiment (1967) showed that rotation of the outer cylinder would stabilize the flow pattern while if the inner cylinder was rotated, particles near the inner cylinder would have a larger centrifugal force and lead to the production of "Taylor vortices." The viscometer cylinders were roughened to avoid slippage between the suspension and the cylinder surfaces. This was accomplished by glueing rubber matting* with an open mesh into the vertical surfaces of the inner and the outer cylinders. A torsion wire of 0.011 in. diameter and 3 in. in length was selected for measuring the torque. One end of the wire was connected to the top of the inner cylinder and the other end was fixed from a pivot at the top, from where the inner cylinder was suspended. The whole arrangement was mounted on an adjustable rigid framwork for ease of adjustment. The outer cylinder was rotated by a variable speed motor** to develop the required angular velocity (Ω) and produce shear in the body of the test fluid. A pointer was attached to the inner cylinder to measure the amount of deflection (θ) recorded over a circular scale (360^{o}) placed below the pointer. An oil damping arrangement was used to minimize the oscillation of the pointer and to reduce the recording time. A schematic diagram of the viscometer is shown in Figure 3.4.

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*No. 3070 Neotex Protective Mesh, distributed by Research Products Corporation, Madison, Wisconsin.

**Zero-Max Variable Speed Motor, Model E, Type N, Zero-Max Industries, 2845 Harriet Avenue South, Minneapolis, Minnesota 55408.

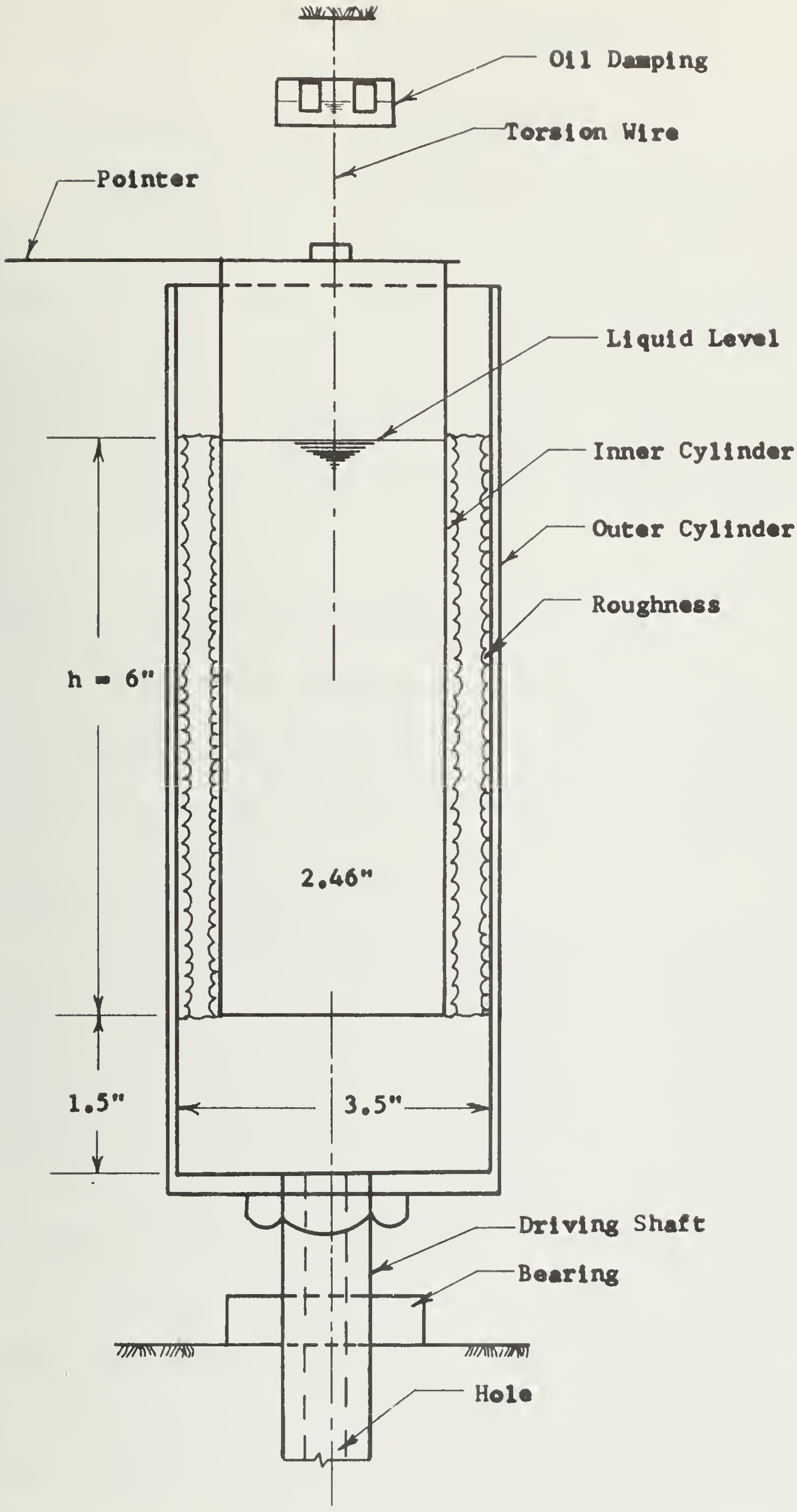

FIGURE 3.4 COAXIAL CYLINDER VISCOMETER

4. LABORATORY PROCEDURES

4.1 Chemical Oxygen Demand (COD) Determination

Extensive COD determinations were carried out in the laboratory for determining the oxidizable part of the organic matter by potassium dichromate. For COD measurement the procedure described in Standard Methods (1965) was followed. Mercuric sulfate was used for complexing any chloride that could be present in the sample. COD measurements were made on unfiltered samples from influent organic waste feed and also from effluent from the units.

4.2 Biochemical Oxygen Demand (BOD) Determination

Five-day BOD values were determined by dilution technique as outlined in Standard Methods (1965). Several BOD and COD values were obtained on the organic feed and a correlation was obtained as discussed.

4.3 Suspended Solids Determination

Total and volatile suspended solids were determined on raw waste samples and mixed liquor in aeration chamber. The glass fiber filter method was used in these determinations as described by Channin *et al.* (1958). Advantages of this technique over the conventional asbestos mat in Gooch crucibles has been discussed by Dick (1965). The procedures consisted of placing glass fiber filters in the Gooch crucible by filtering a few ml of water. The crucible was then placed in an oven at 103°C for 1 hr in small individual desiccators. After drying, the desiccators were capped, cooled and the crucible weighed. Then a sample was filtered and the above procedure repeated. Volatile suspended solids were determined by firing the crucible at 600°C.

4.4 Dehydrogenase Enzyme Activity Measurement

Measurement of dehydrogenase enzyme as proposed by Ford et al. (1966) was used as a method for determining sludge activity.

4.4.1 Reagents

1. Tris-HCl Buffer, 0.05 M, pH 8.4

   Add 6.037 g of tris buffer and 20 ml 1.0 N HCL to one ℓ of distilled water.

2. TTC Glucose Reagent

   Dissolve 0.2 g TTC and 1.5 g of glucose in 100 ml distilled water. Store the solution in the dark at 2°C and make up fresh weekly.

3. Absolute Ethyl Alcohol

4. Triphenyl Formazan (TF) Standard

   Dissolve 0.3 g of TF (mol. wt. 300.4) into 500 ml of ethyl alcohol. One, two, three, four, and five ml samples of this solution are distilled to 50 ml with ethyl alcohol to give standard solutions containing 2.0, 4.0, 6.0, 8.0 and 10.0 micromoles (μM) of TF per 50 ml.

4.4.2 Procedure

Five ml of tris-buffer was added to each of 4 test tubes (50 ml or more capacity). Five ml of mixed liquor activated sludge of known volatile solid concentration were added to each of these. The temperature of these mixtures was brought to 37°C rapidly in a constant temperature bath. One ml of TTC solution was added to three test tubes and 1 ml distilled water was added to the fourth test tube which served as a control. The solutions were kept at 37°C in a constant temperature bath for 15 min

and at the end of this period of incubation the reaction was stopped by adding ethyl alcohol to a final volume of 50 ml in each of the test tubes. The contents were then thoroughly mixed, filtered and the percent transmission was measured by a spectrophotometer* at 490 $m\mu$ using the control as a blank. The average of three samples was used. The amount of TF produced was determined from the standard curve. The amount of TF produced per unit volatile suspended solid was taken as a measure of active cells present in a biomass.

The standard curve was drawn from TF dilutions as explained before by taking percent transmission at 490 $m\mu$. The standard curve obtained is shown in Figure 4.1.

Several additional precautionary measures were taken in this experiment; the details have been described by Ford et al. (1966).

4.5 Calibration of Viscometer and Measurement of Rheological Properties of Activated Sludge

The physical dimensions of the viscometer are shown in Figure 3.4. Distilled water at 80°F was used as the calibration fluid. The fluid was conveyed through the bottom of the viscometer into the annular space between the cylinders up to a depth of 7½ in. Wang (1967) found that distilled water had a viscosity similar to that of activated sludge and he suggested distilled water as a calibration fluid for measuring physical properties of activated sludge.

The outer cylinder was rotated at various angular velocities (Ω) as measured by revolutions of the outer cylinder per min (rpm) and the

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*Beckman D. U. Spectrophotometer, Beckman Instruments, Inc., Fullerton, California.

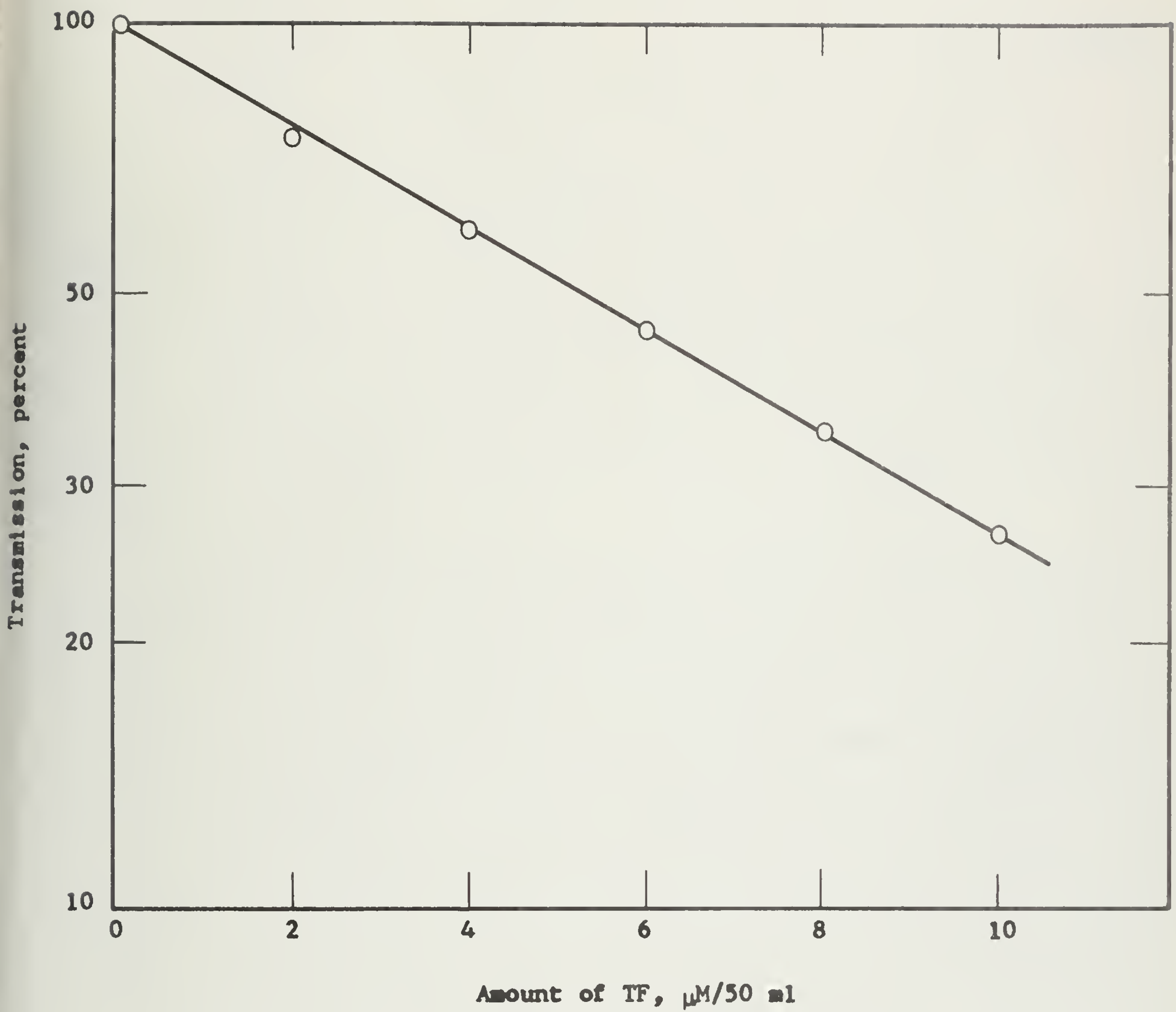


FIGURE 4.1 STANDARD CURVE FOR MEASUREMENT OF DEHYDROGENASE ENZYME

deflection (θ) of the pointer recorded for each angular velocity. The rotational speeds (Ω) were plotted against the deflections (θ). Wang (1967) in his experiment found that the end effect depended on the viscosity of the test fluid. He showed that 95 percent glycerol had a different end effect than distilled water because of difference in viscosity, and similarly activated sludge had an end effect different than any of the test fluids. However, the viscosity of activated sludge was closer to that of distilled water. In order to evaluate the end effect (h_o), the torsional constant of the suspended wire (α), and effective thickness of rubber matting (δ) the following procedure was followed as described by Wang (1967):

A series of curves were obtained by plotting the rotative speed (Ω) and deflection (θ) for different depths of fluid (h) in the viscometer. The depth of fluid (h) was measured from the bottom of the inner cylinder as indicated in Figure 3.4. The same procedure was repeated with roughness on the inner cylinder and also with the roughness on both the inner and outer cylinders. Figure 4.2 shows the plots of rotative speeds (Ω) and deflections (θ) for various depths of fluid (h), with roughness on the inner cylinder. Similar plots were obtained for roughness on both the cylinders.

Dick (1967) showed that, in determining the viscosity of any Newtonian fluid, all geometric characteristics of a particular viscometer could be combined into a single constant (K_A). Viscosity (μ) could be calculated from the expression

$$\mu = K_A \frac{T}{\Omega} \tag{7}$$

where Ω is the relative angular velocity between cylinders as measured by number of rotations per min (rpm). T is the torque produced due to shear

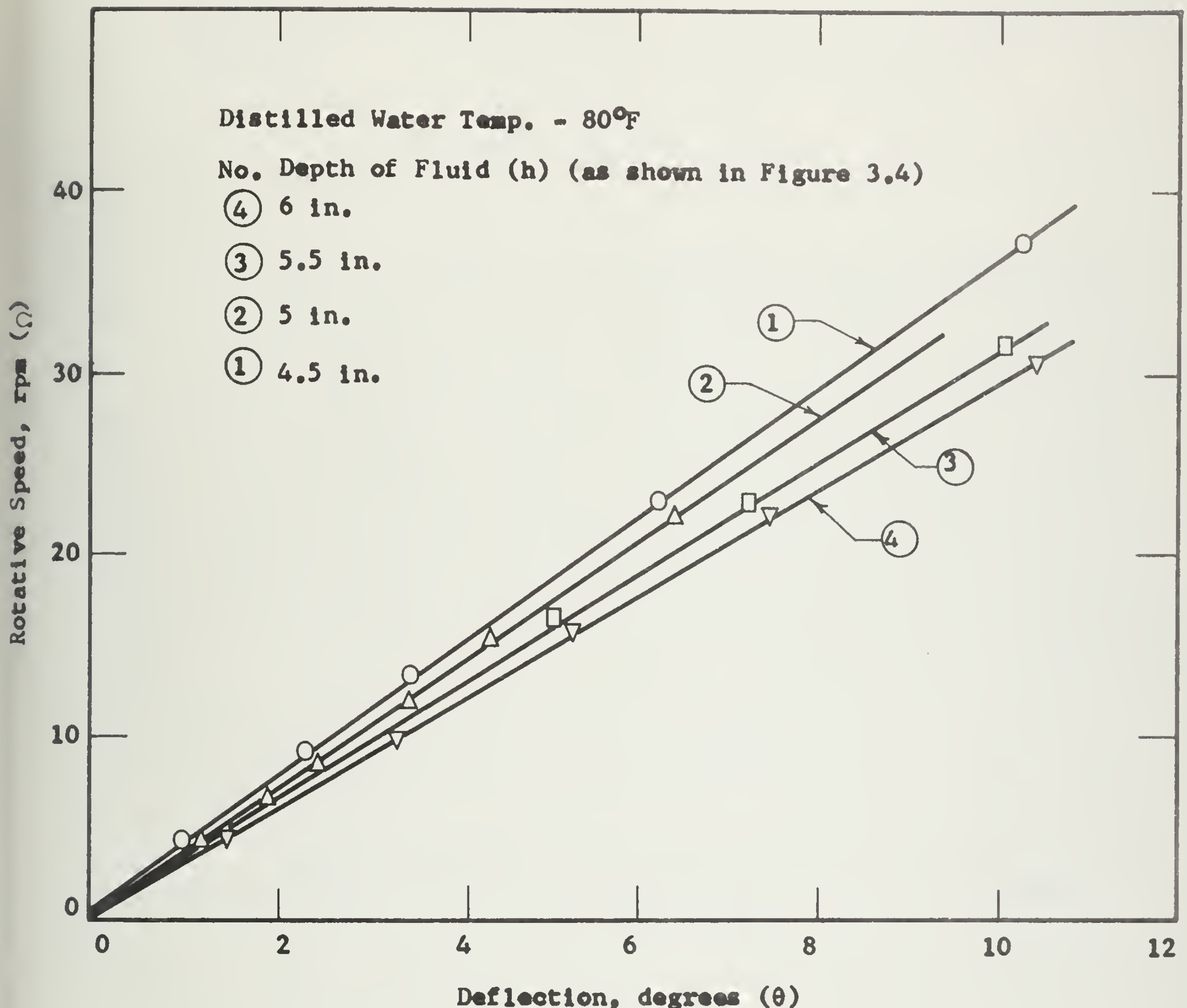


FIGURE 4.2 PLOT OF ROTATIVE SPEED VS DEFLECTION WITH DISTILLED WATER AS TEST FLUID

in the body of fluid and could be measured by the expression:

$$T = \alpha\theta \tag{8}$$

where α is the torsional constant of the wire and θ is the angular deflection as recorded. K_Λ can be calculated from the following expression:

$$K_\Lambda = \frac{1}{4\pi(h + h_o)}\left(\frac{1}{R_i^2} - \frac{1}{R_o^2}\right) \tag{9}$$

where h is the depth of suspension in the viscometer, h_o is the end effect produced, and R_i and R_o are radii of inner and outer cylinders respectively.

In order to determine the end effect plots of θ/Ω vs h were made with roughness on the inner cylinder and on both the cylinders. The plots are shown in Figure 4.3 (a) and (b). Wang (1967) showed that the value of the spring constant (α) and effective thickness of the roughness (δ) can be computed from the slope of the θ/Ω vs h curves and are given by the following expressions:

(1) for roughness on the inner cylinder

$$\frac{\theta/\Omega}{h + h_o} = 8\pi^2 \frac{\mu}{\alpha}\left[\frac{1}{(R_i + \delta)^2} - \frac{1}{R_o^2}\right]^{-1} \tag{10}$$

(2) for roughness on both cylinders

$$\frac{\theta/\Omega}{h + h_o} = 8\pi^2 \frac{\mu}{\alpha}\left[\frac{1}{(R_i + \delta)^2} - \frac{1}{(R_o - \delta)^2}\right]^{-1} \tag{11}$$

where μ is the viscosity of test fluid and δ is the effective thickness of the roughness. By solving these equations the values of α and δ were obtained.

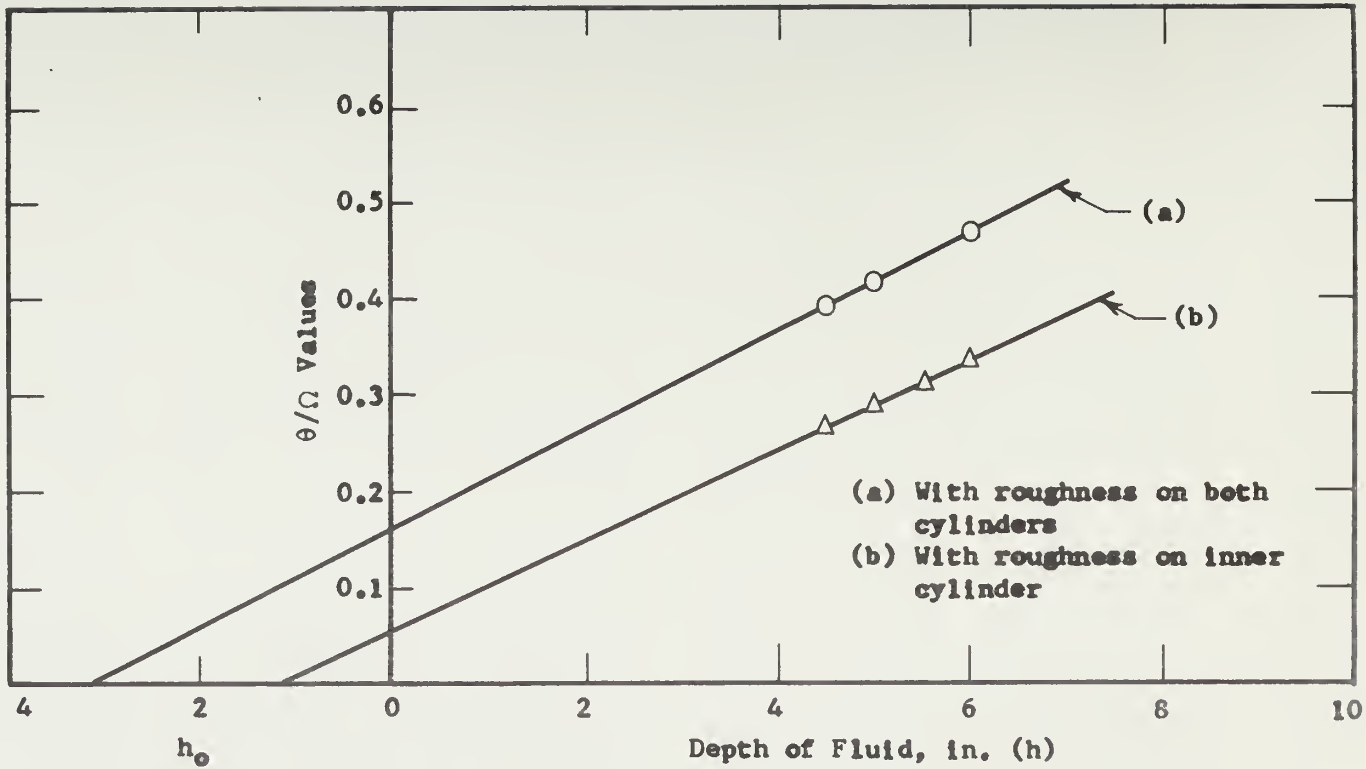


FIGURE 4.3 DETERMINATION OF END EFFECT (h_o) WITH ROUGHNESS ON INNER AND OUTER CYLINDERS

4.5.1 Experiment with Activated Sludge

The activated sludge was transferred from the aeration unit as quickly as possible through the hole at the bottom of the viscometer to a depth of 7½ in. This depth of sludge (h = 6 in.) was maintained throughout the experiment.

Activated sludge has the property of settling in the viscometer, so as soon as the activated sludge was put in the viscometer it was aerated for 10 to 15 sec to disperse the sludge solids. Then it was allowed to reflocculate. Dick and Ewing (1967) showed that a reflocculation time of 45 sec was enough. The damping arrangement was adjusted in such a way that the readings could be taken after 45 sec of flocculation. The rotative speed (Ω) was determined by an automatic counter and a stop watch. The values of rotative speed and deflection were plotted and the curves fitted by method of least squares.

For determining the plastic viscosity and yield strength of activated sludge plots were made between rotative speeds (Ω) and angles of deflection (θ). The values of torque were determined from values of θ as described before. Yield strength (τ_y) was determined from the torque at zero angular velocity. Dick (1967) showed that the yield strength could be measured conveniently by the following expression

$$\tau_y = K_B T_x \qquad (12)$$

where T_x does not have any physical significance but could be easily determined from the extrapolate of the straight portion of θ vs Ω curve and K_B is a constant as given by the following expression

$$K_B = \frac{K_A}{\log_e \frac{R_o}{R_i}} \qquad (13)$$

and could be determined from the physical dimension of the viscometer. Similarly the plastic viscosity (η) was obtained by the following expression

$$\eta = K_A \frac{T - T_x}{\Omega} \qquad (14)$$

where T is torque at any point on the curve. Several plots of θ vs Ω are shown in the subsequent chapters.

The values of the constants described in this chapter are as follows:

Torsional Constant α = 1.78×10^{-6} ft-lb/degree rotation

Instrument Constant K_A = 5.45 ft^{-3}

Instrument Constant K_B = 15.6 ft^{-3}

Effective Thickness of Roughness δ = 0.13 in.

5. RESULTS AND DISCUSSION

5.1 Changes in Yield Strength of Activated Sludge under Different Biological Loadings

Activated sludge was acclimated in the laboratory at different organic loadings. The yield strength of the sludge at the different organic loadings was determined by the viscometer as shown in Figures 5.1, 5.2 and 5.3. The figures show plots of rotational speed (Ω, rpm) against the angle of deflection (θ, degrees) for each of the organic loadings. The curves were fitted by the method of least squares. Yield strength value was calculated from torque at zero rate of shear as determined from the intercepts obtained by the extrapolate of the straight line portion of the curve as discussed before. The nonlinear portion of the curves at low rates of shear is due to the fact that with plastic substances shearing stress at the surface of the rotating cylinder must be exceeded before any rotation occurs. The shearing will cease at a radius where the local shearing stress will be exceeded by the yield strength. The substance outside this critical radius will behave as a solid and that within this critical radius will behave as a liquid. This will cause a higher rotative speed compared to the shear stress and the curve is nonlinear. However, when the critical radius is exceeded and whole mass of the fluid is sheared, the shear stress will be proportional to the rate of shear and a linear relationship is obtained. The yield strength is obtained by extrapolating the straight portion of the curve on the θ axis as explained before.

Each curve in the figures represents a suspension at a particular suspended solid concentration at a particular loading. The concentrations are given in Table 5.1.

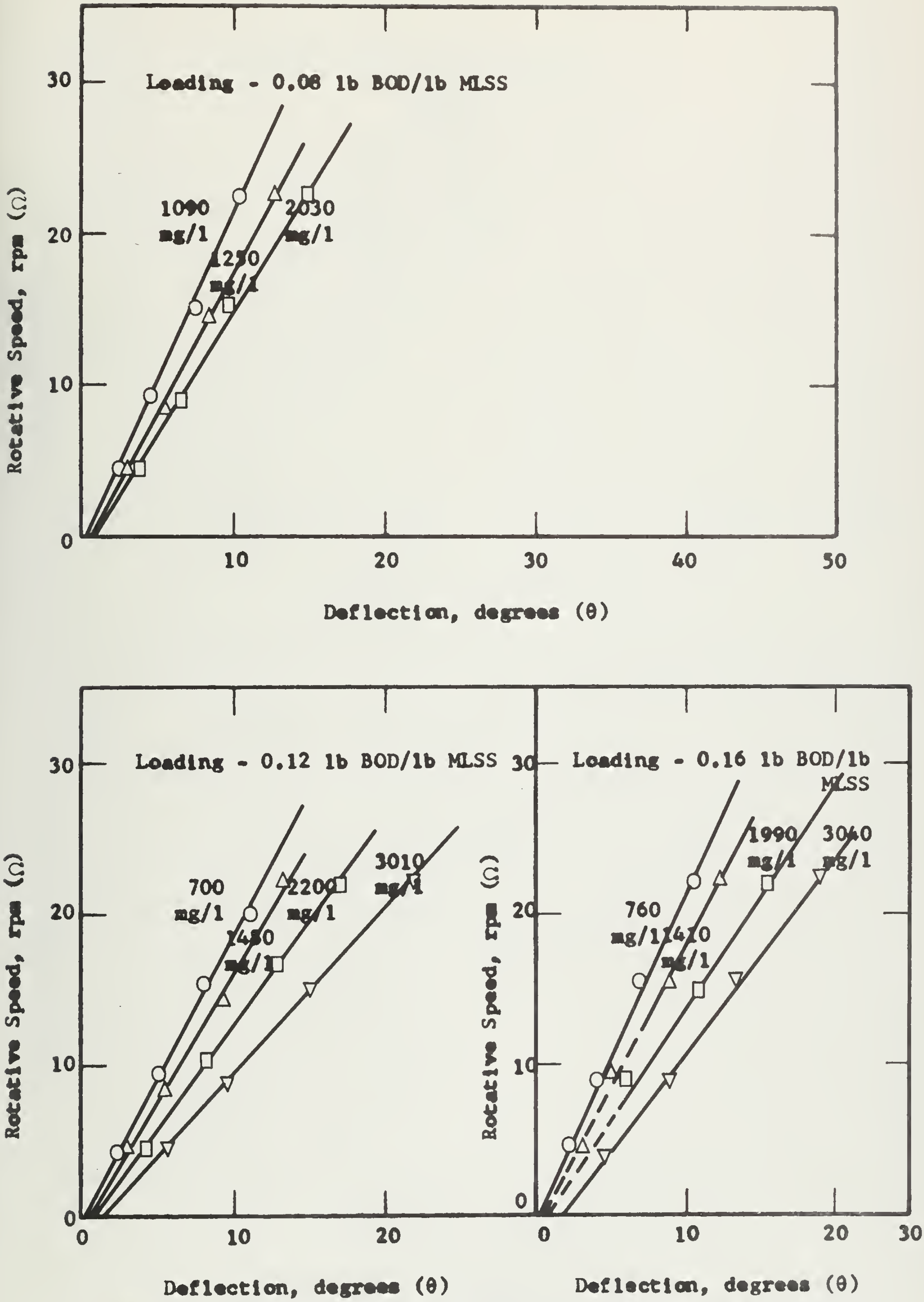
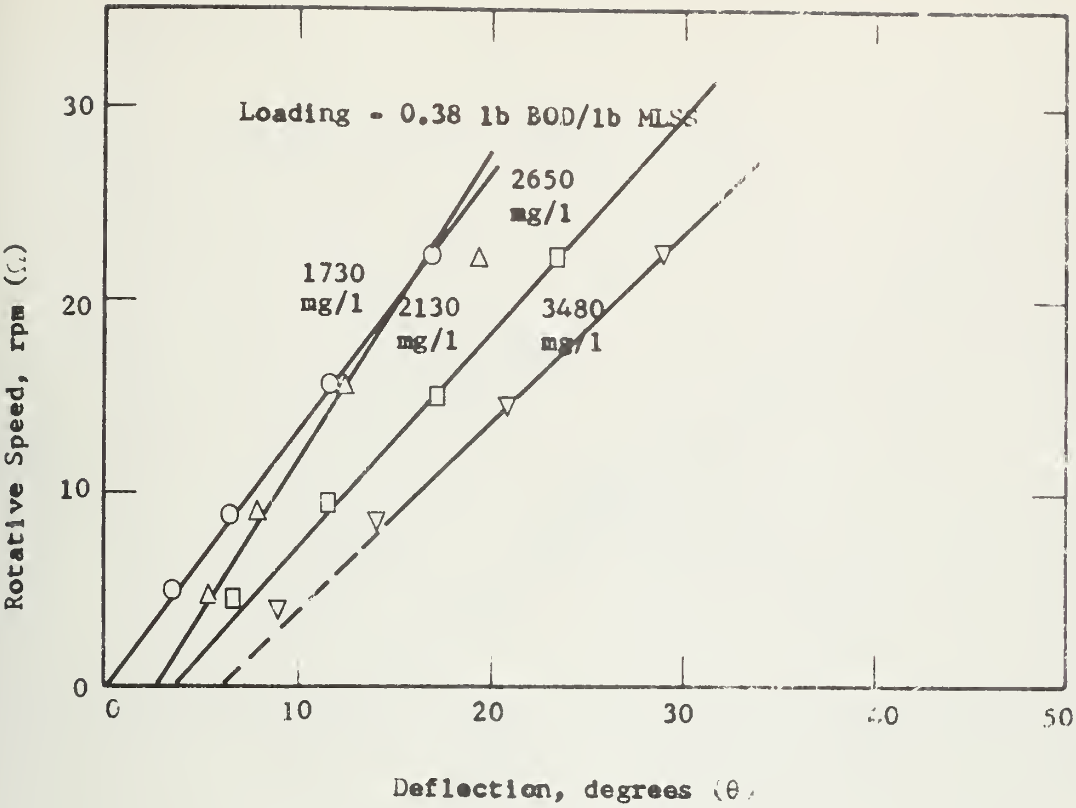


FIGURE 5.1 DETERMINATION OF RHEOLOGICAL PROPERTIES OF ACTIVATED SLUDGE AT DIFFERENT LOADINGS



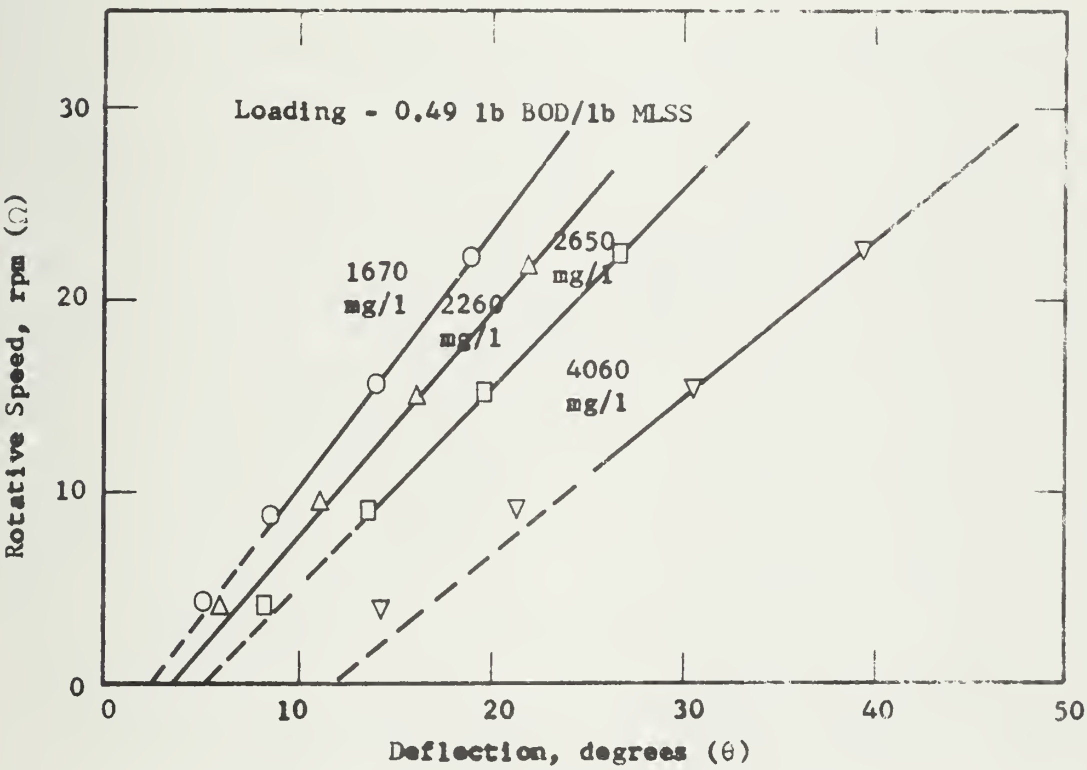


FIGURE 5.2 DETERMINATION OF RHEOLOGICAL PROPERTIES OF ACTIVATED SLUDGE AT DIFFERENT LOADINGS

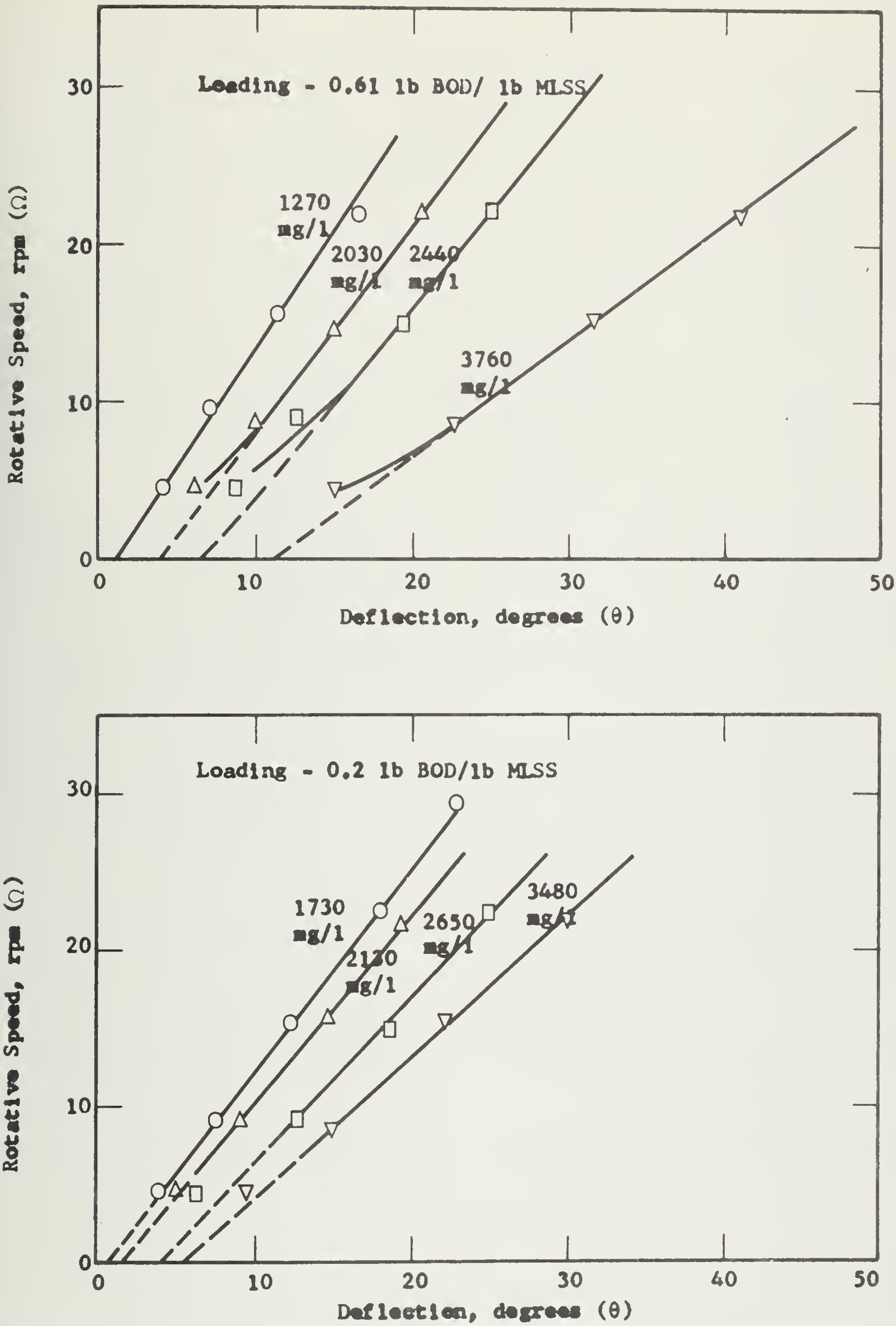


FIGURE 5.3 DETERMINATION OF RHEOLOGICAL PROPERTIES OF ACTIVATED SLUDGE AT DIFFERENT LOADINGS

Loading lb BOD/lb MLSS (Lf)	Intercept degrees (θ')	Yield Strength lb/ft^2 (θ' x x K_B x 10^5)	Suspended Solids Concentration mg/ℓ
Lf (1) = 0.08	0.35	0.97	1090
	0.50	1.39	1250
	0.80	2.22	2030
Lf (2) = 0.12	1.8	5.0	3010
	0.9	2.5	2200
	0.6	1.67	1480
	0.3	0.84	700
Lf (3) = 0.16	1.9	5.3	3040
	1.0	2.78	1990
	0.75	1.95	1410
	0.5	1.38	760
Lf (4) = 0.2	5.6	15.5	3410
	4.0	11.1	2590
	1.8	5.0	1950
	0.8	2.22	1520
Lf (5) = 0.38	6.0	16.7	3480
	3.8	10.6	2650
	2.9	8.05	2130
	0.6	1.67	1730
Lf (6) = 0.49	11.8	32.8	4060
	5.3	14.2	2650
	3.5	9.73	2260
	2.3	6.4	1670
Lf (7) = 0.61	11.1	30.8	3760
	6.3	17.3	2440
	4.0	11.1	2030
	1.6	4.50	1270

Table 5.1 CALCULATION OF YIELD STRENGTH AT DIFFERENT ORGANIC LOADINGS

Table 5.1 also shows the intercepts (θ') obtained on the θ-axis for each curve and the corresponding yield strength values are shown against the concentration of suspended solids at different organic loadings.

In order to determine the changes in yield strength values due to biological effects only, the changes due to suspended solid concentrations of the sludge were determined first as shown in Figure 5.4. Dick and Ewing (1967) showed that the yield strength of activated sludge changes due to change in concentrations of suspended solids. The plots of yield strength against concentration as shown in Figure 5.4, show that for a particular concentration the yield strength values are different for different organic loadings. Each curve in Figure 5.4 is numbered and corresponds to a particular loadings as shown in Table 5.1.

Figure 5.5 shows the changes in yield strength values due to biological loadings. The effect of biological loadings on yield strength at four different concentrations are shown. It can be seen from the figures that at lower concentrations of suspended solids yield strength is related directly to the biological loading. This is true within the range of loading as shown in the figure. At concentrations of 2500 mg/ℓ and above the relationship is nonlinear or in other words the change in yield strength is more significant with increase in organic loading. However, no definite relationship could be obtained at these higher concentrations between yield strength and organic loadings.

No data could be obtained above the range of loading shown in the figure. So nothing can be concluded about the relationship above a loading of 0.61 (lb BOD/lb of suspended solids). At higher loadings solids were carried over with the effluent. This could be due to excessive hydraulic loading. No microscopic study was made to determine the predominance of any

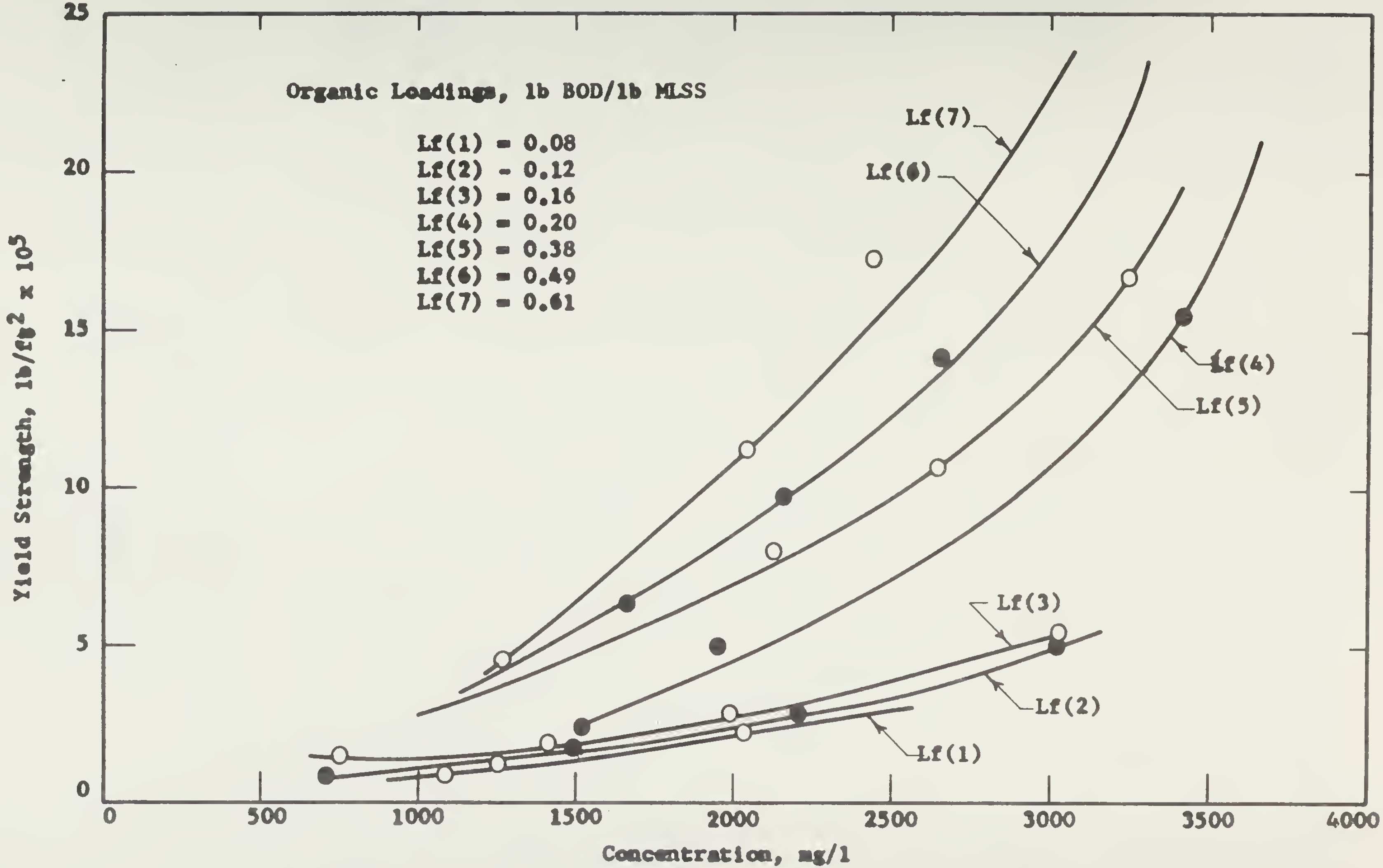


FIGURE 5.4 CHANGES IN YIELD STRENGTH DUE TO DIFFERENT ORGANIC LOADINGS

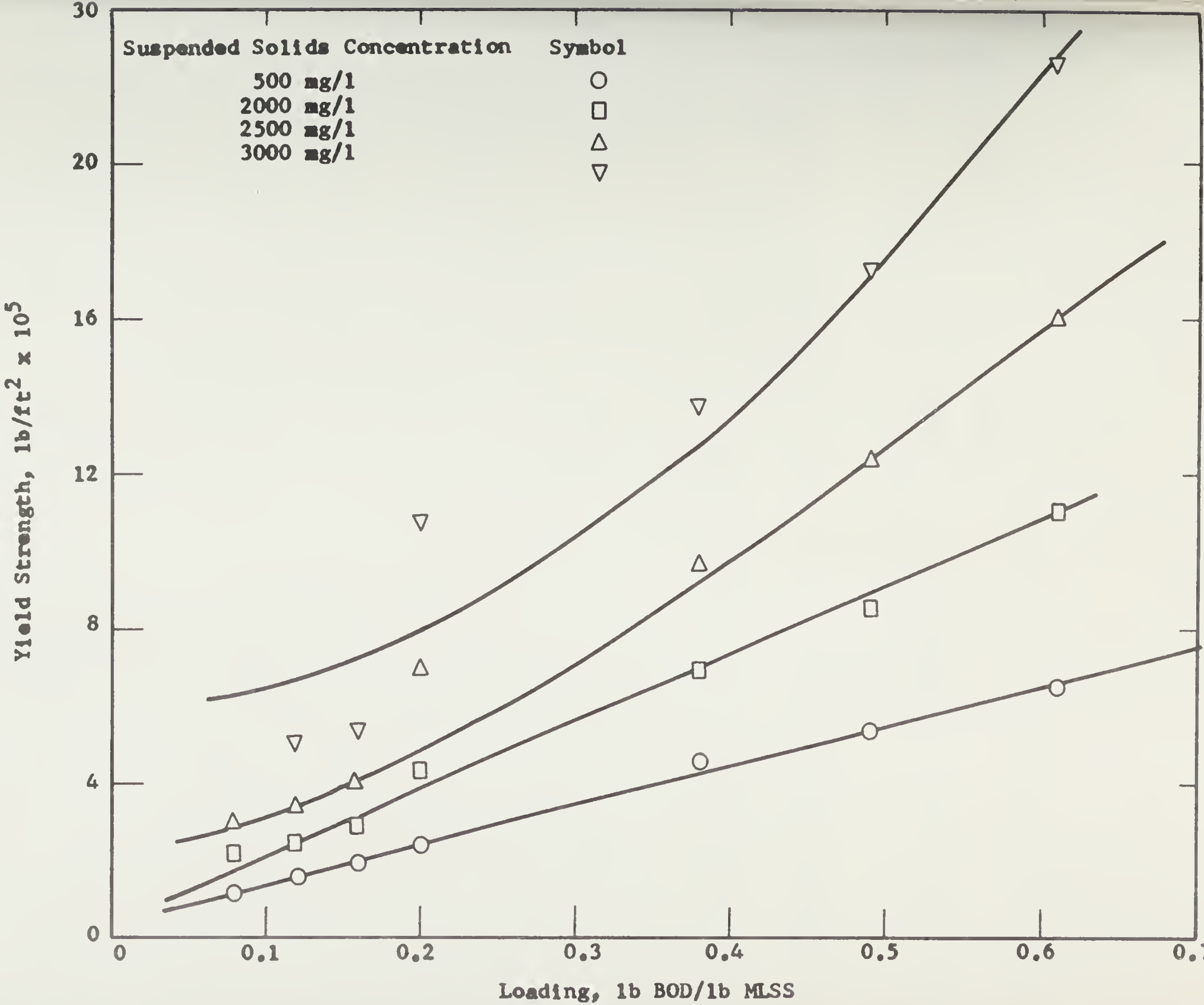


FIGURE 5.5 CHANGES IN YIELD STRENGTH UNDER DIFFERENT LOADINGS

particular species of microorganisms in the mixed liquor at the highest loading or any sludge volume index measurement was made to see whether sludge bulking occurred at this loading. However, there are enough evidences in the literature to show that at a loading above 0.7 (lb BOD/lb sludge) sludge bulking occurred. The work of Ford and Eckenfelder (1966) can be mentioned in this connection.

The above relationships may be different under different environmental conditions and with different organic wastes.

5.2 Changes in Dehydrogenase Enzyme Activity under Different Biological and Physical Conditions

Enzyme activity as measured by the amount of TF produced (reduced form of TTC) per mg volatile suspended solids is shown in Table 5.2. Ford *et al.* (1966) showed that the amount of TF produced per mg volatile suspended solids to be a measure of sludge activity. Table 5.2 shows the calculated amounts of TF produced per unit weight of the sludge, for different loadings. As discussed in the experimental procedure a total volume of 50 ml sample as shown in the table represents 5 ml of activated sludge. The amount of TF produced per 5 ml of sludge as determined from the standard curve is shown in column (4) of Table 5.2. Column (5) shows the amount of TF produced, per mg volatile suspended solids, which is plotted against organic loadings in Figure 5.6. It can be seen from the figure that with increase in organic loading there is increase in biological activity per unit weight of the biological mass. Ford and Eckenfelder (1966) described the measurement of dehydrogenase enzyme as a good parameter of sludge activity. The increase of dehydrogenase activity with organic loading using domestic sewage followed the same relationship as set forth by Ford and Eckenfelder (1966).

(1) Loading (1b BOD/1b MLSS)	(2) Total Susp. Solids (mg/ℓ)	(3) Total Vol. Susp. Solids (mg/ℓ)	(4) TF Produced per 50 ml Volume (μm)	(5) TF Produced per mg Vol. Susp. Solids (μm)
0.22	2143	1540	1.35	0.175
0.35	2552	1900	1.98	0.260
0.36	1967	1482	2.05	0.271
0.44	2987	2250	2.79	0.310
0.52	1783	1320	2.70	0.355
0.59	2363	1710	3.10	0.361
0.70	2983	2333	4.42	0.381

Table 5.2 CALCULATED VALUES OF DEHYDROGENASE ACTIVITY AS MEASURED BY SPECTROPHOTOMETER

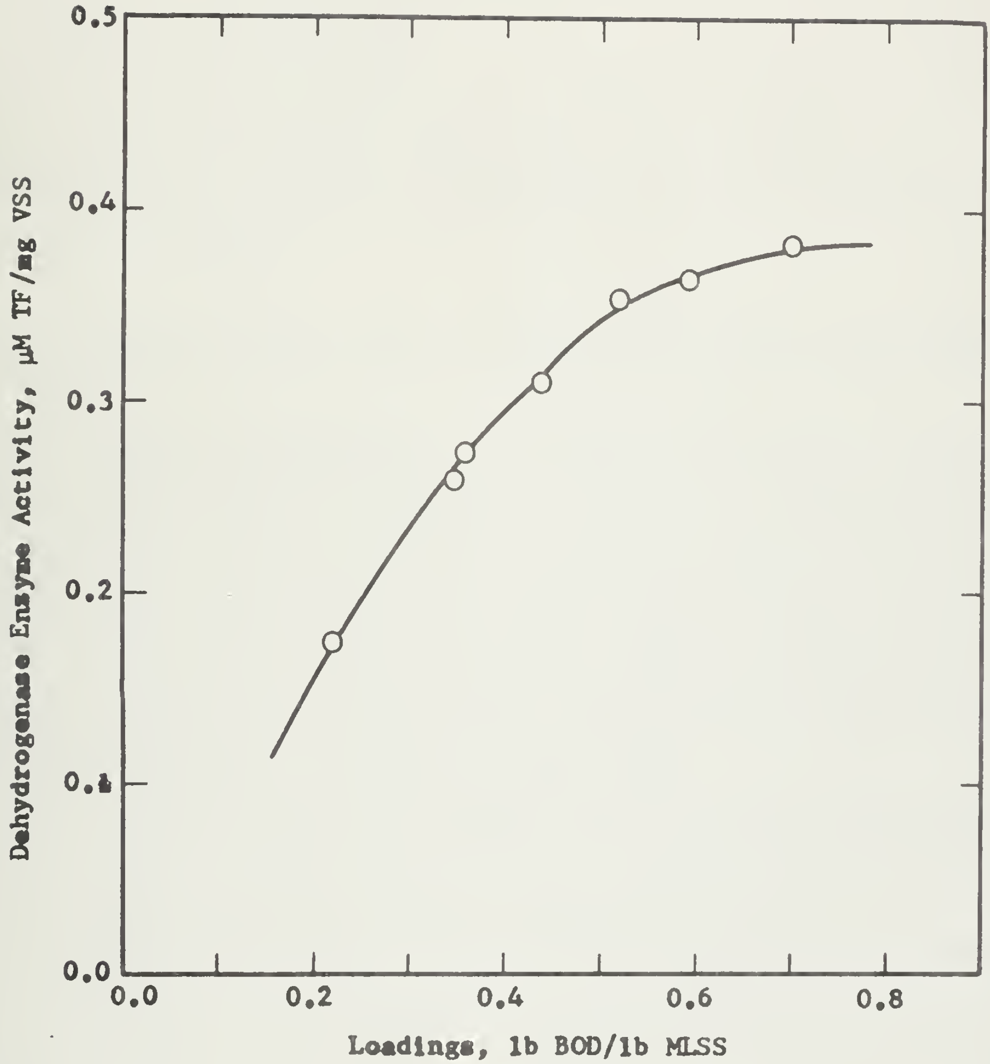


FIGURE 5.6 DEHYDROGENASE ENZYME ACTIVITY UNDER DIFFERENT LOADINGS

Figure 5.7 shows as plots of dehydrogenase enzyme activity against yield strength value under different concentrations of suspended solids. The data were obtained from the curves shown in Figures 5.5 and 5.6. It can be seen that yield strength values could be related to sludge activity as measured by dehydrogenase enzymes. The changes in yield strength values with respect to the dehydrogenase enzyme activity become more at higher concentrations. The same phenomenon was observed in the plots of yield strength against biological loadings.

5.3 Changes in Physical Properties of Activated Sludge during Endogenous Respiration

This study was undertaken to investigate the changes in physical properties and other parameters of activated sludge with prolonged aeration times. The feeding of organic substrate in the laboratory units was stopped and the mixed liquor aerated for several days. Measurements of yield strength, plastic viscosity, solids and dehydrogenase enzymes were made over an interval of 24 hr. The data obtained are given in Table 5.3.

Measurements of physical properties were made by the viscometer as before and are shown in Figures 5.8, 5.9, 5.10, 5.11, and 5.12. The curves were fitted by the method of least squares and the equations for the curves thus obtained are shown in the figures. As discussed before the intercepts on the θ-axes were converted to yield strength values and the slopes of the curves were converted to plastic viscosities.

Endogenous respiration, also known as auto-oxidation, is defined as a process in which the biological mass produced due to synthesis is consumed by self-oxidation in which case the sludge accumulation gradually decreases with time of aeration. This can be seen in Figures 5.13 and 5.15. The total suspended solids and volatile suspended solids decreased with time.

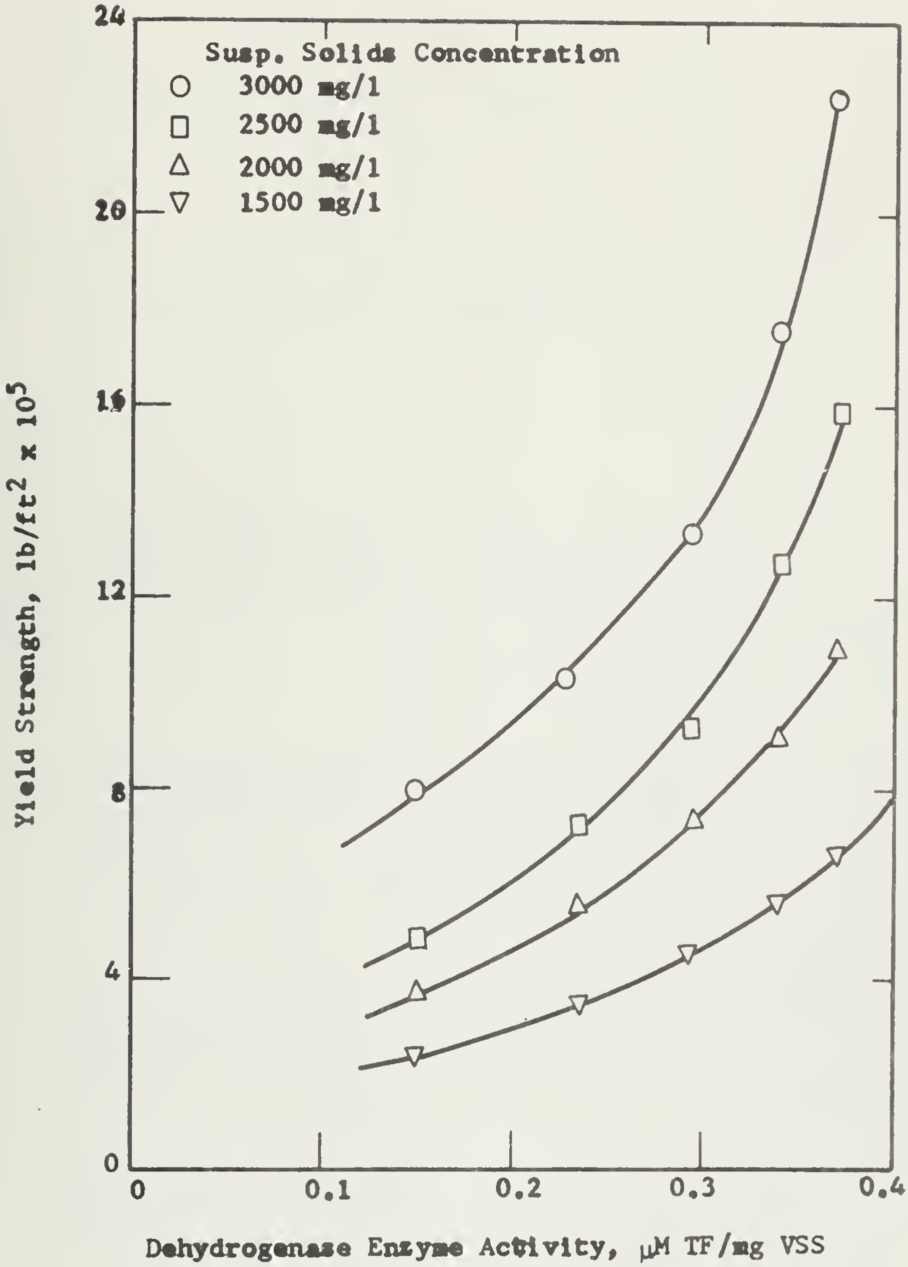
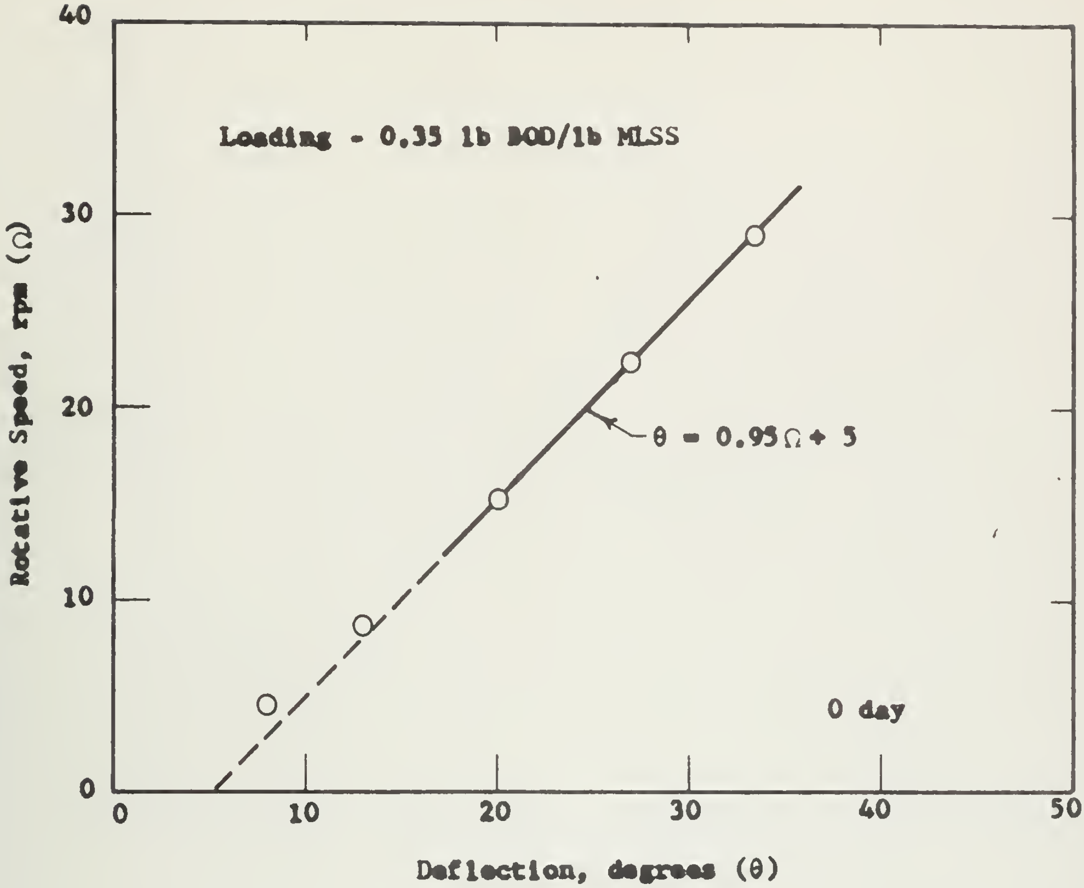


FIGURE 5.7 DEHYDROGENASE ENZYME ACTIVITY VS YIELD STRENGTH AT DIFFERENT CONCENTRATIONS

Loading (lb BOD/lb MLSS)	Time (days)	Total Susp. Solids (mg/ℓ)	Volatile Susp. Solids (mg/ℓ)	Dehydrogenase Activity (TF Produced per mg Vol. Susp. Solids) (μm)	Yield Strength (lb/ft^2)	Apparent Viscosity ($lb\text{-}sec/ft^2$)
0.35	0	1590	1190	0.218	13.9	9.2
	1	1310	980	0.202	8.61	7.8
	2	--	--	--	14.7	7.8
	3	1280	950	0.126	7.23	7.14
	4	1118	835	0.096	--	--
	5	1090	818	--	--	--
	6	1050	790	0.025	--	--
	7	1010	740	0.027	1.03	7.14
0.52	0	1955	1470	0.272	21.7	11.1
	1	2000	1500	0.213	21.1	8.82
	2	2100	1540	0.13	18.5	8.82
	3	1440	1120	0.14	5.12	8.66
	4	1530	1090	0.128	--	--
	5	1402	1050	--	--	--
	6	1400	1050	0.123	--	--
	7	1380	1030	0.116	0.28	6.38

Table 5.3 ENDOGENOUS RESPIRATION DATA



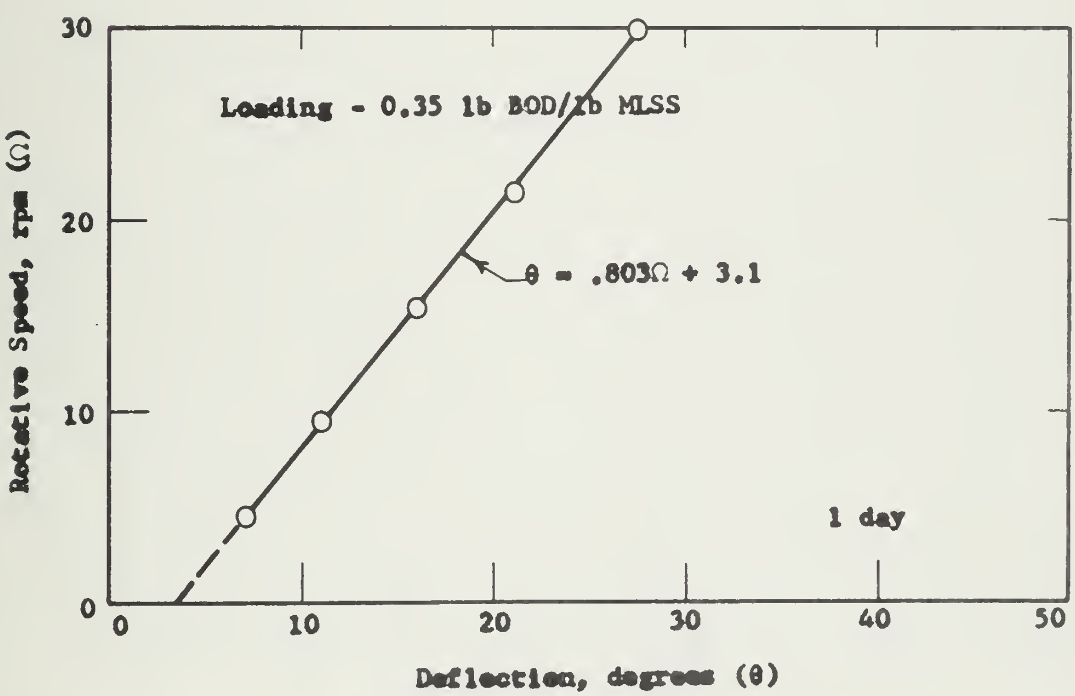
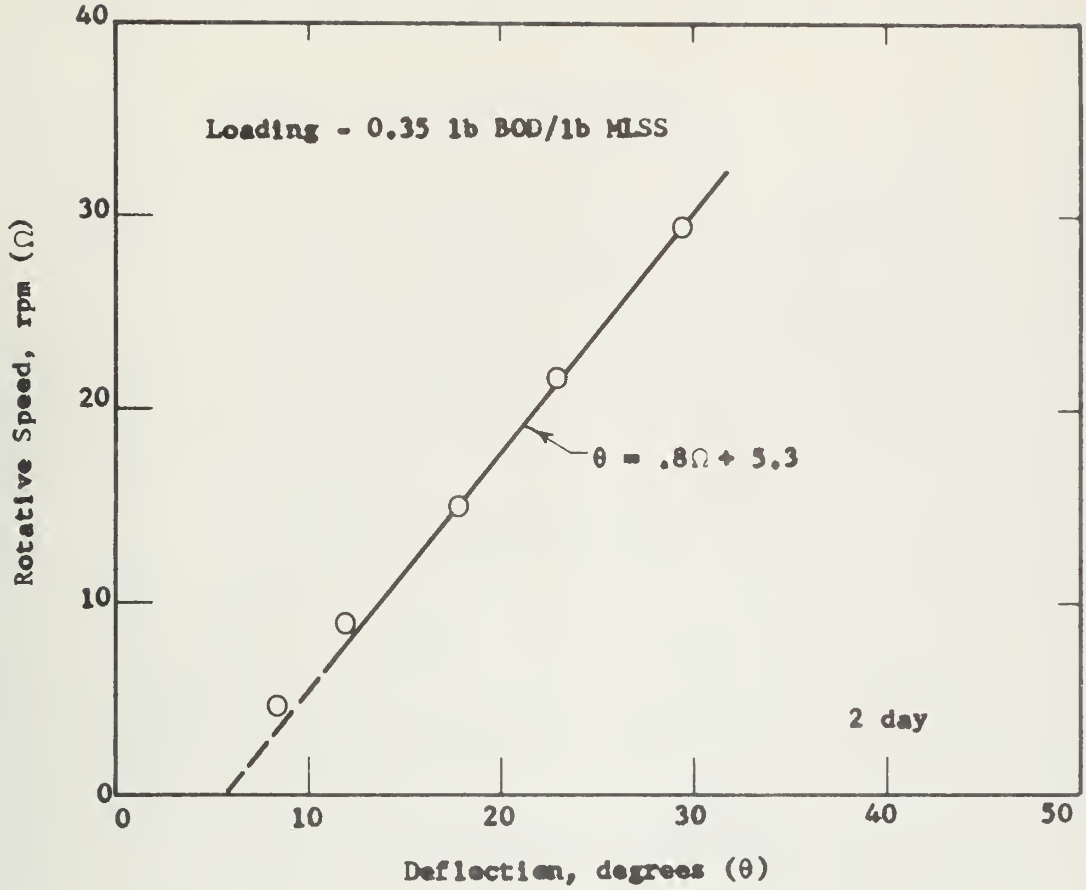


FIGURE 5.8 DETERMINATION OF PHYSICAL PROPERTIES IN ENDOGENOUS PHASE



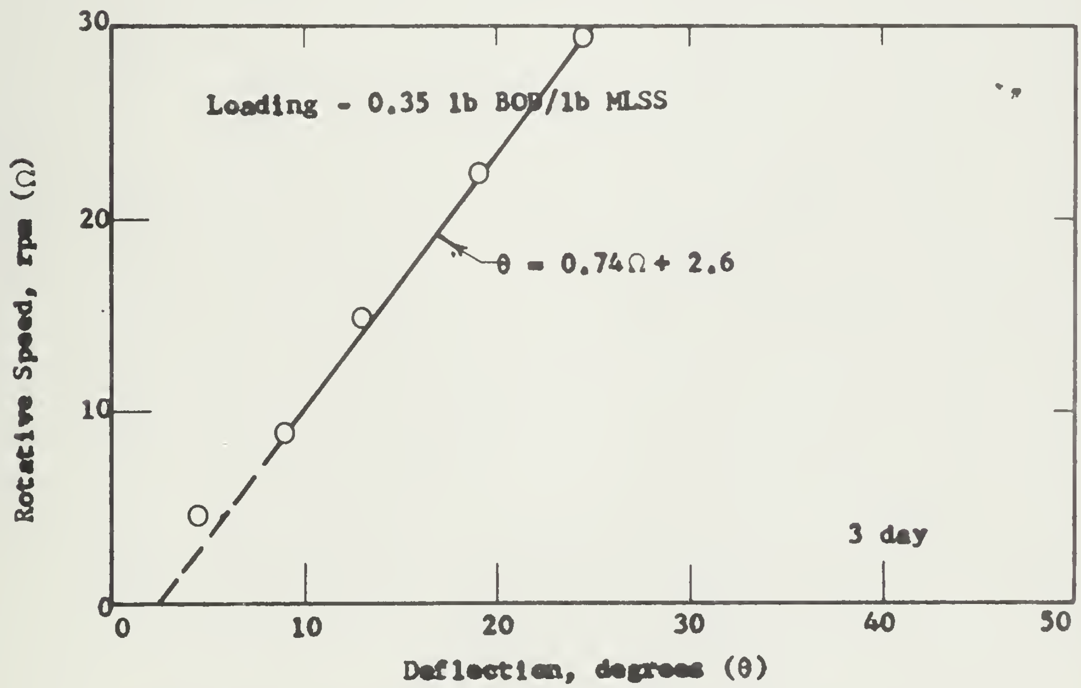
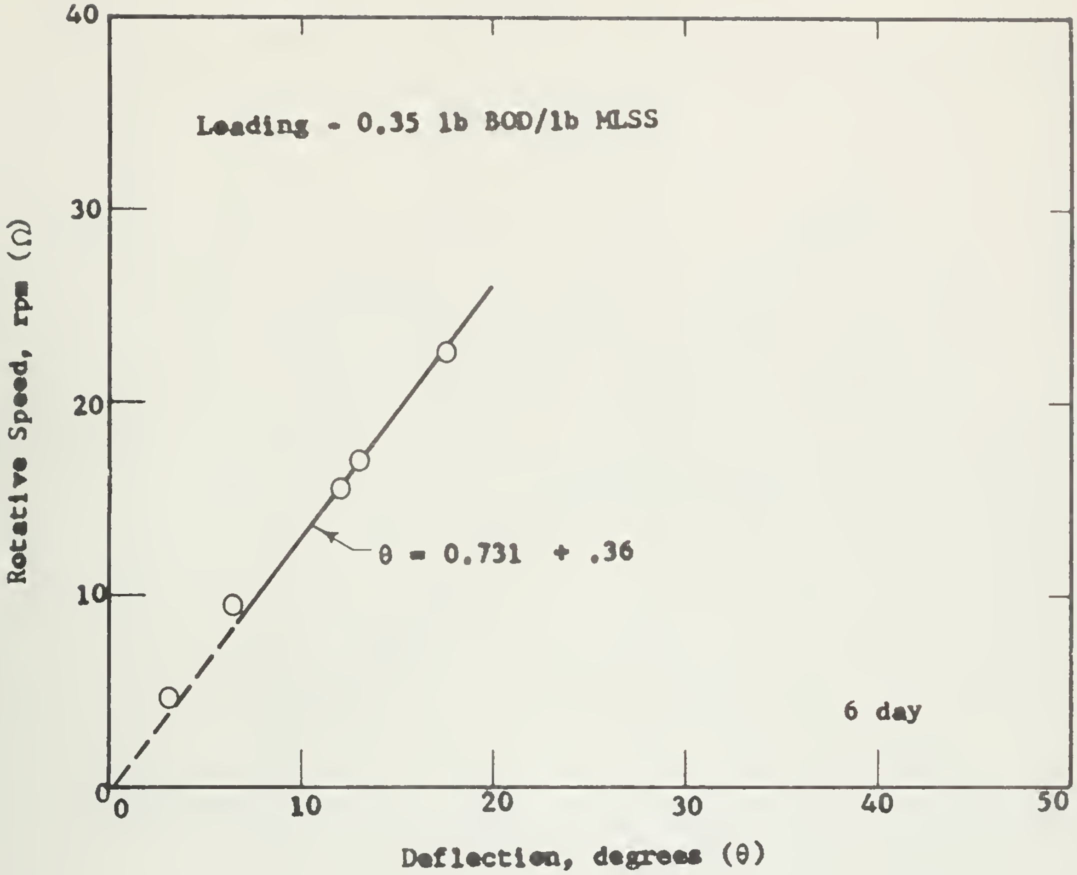


FIGURE 5.9 DETERMINATION OF PHYSICAL PROPERTIES IN ENDOGENOUS PHASE



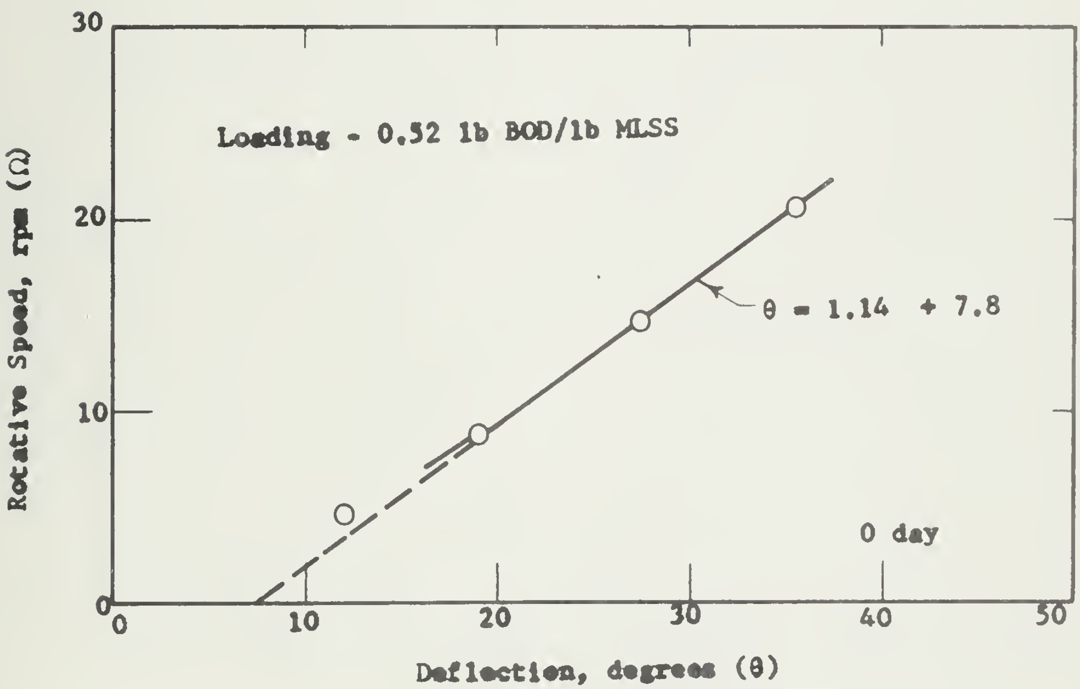
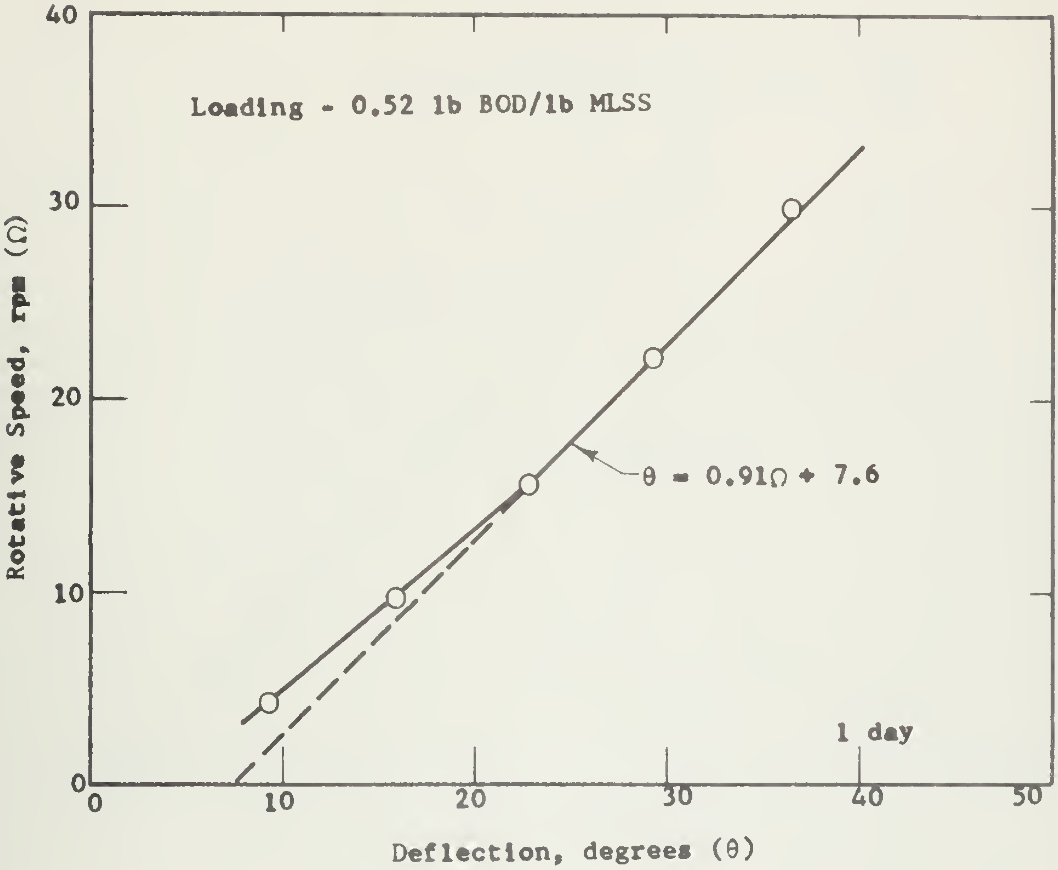


FIGURE 5.10 DETERMINATION OF PHYSICAL PROPERTIES IN ENDOGENOUS PHASE



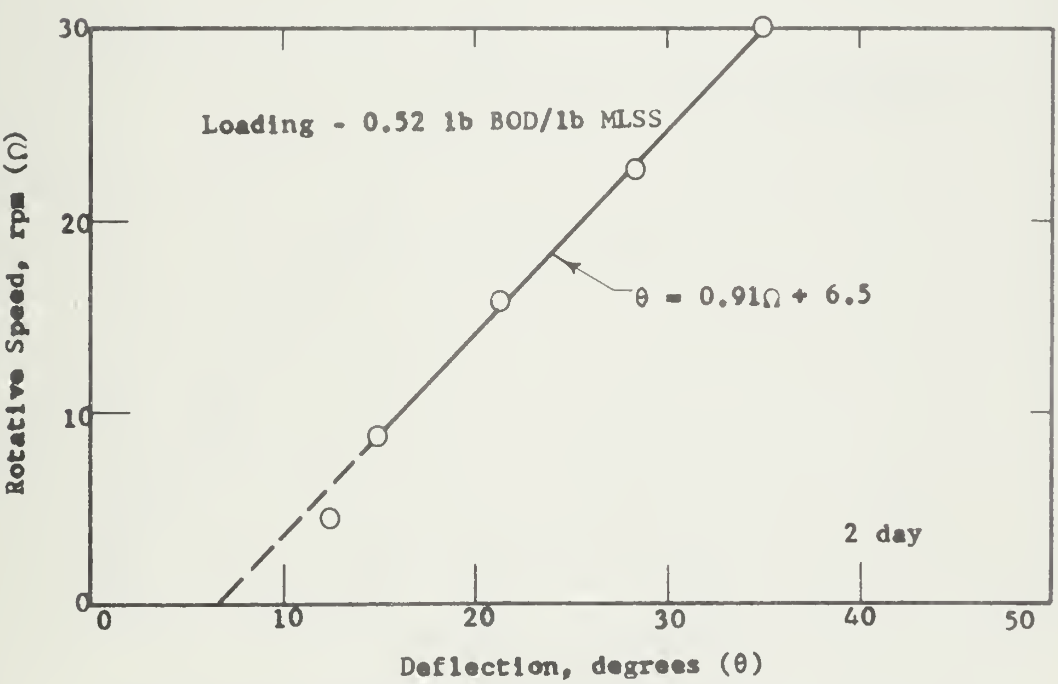
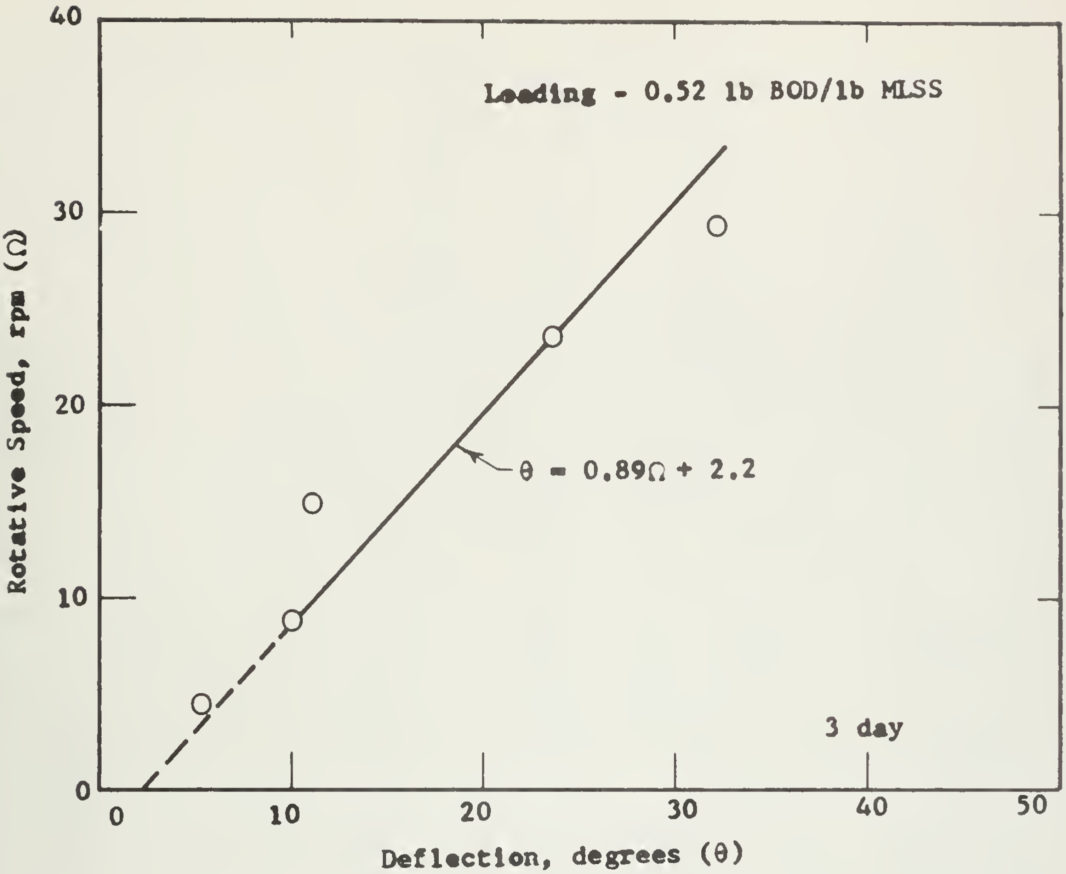


FIGURE 5.11 DETERMINATION OF PHYSICAL PROPERTIES IN ENDOGENOUS PHASE



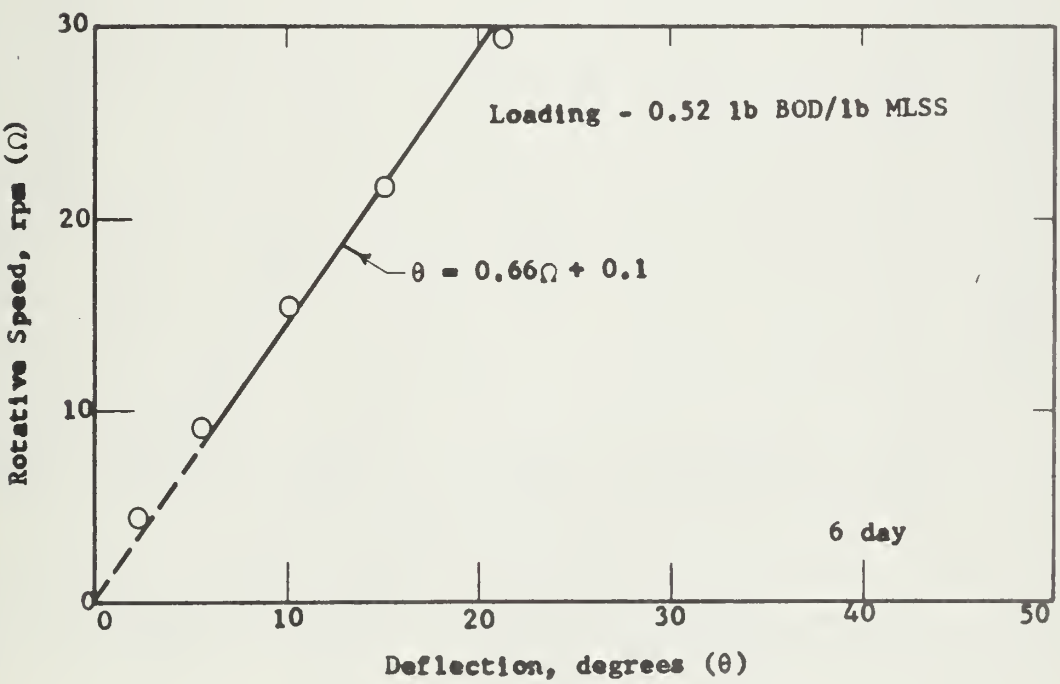


FIGURE 5.12 DETERMINATION OF PHYSICAL PROPERTIES IN ENDOGENOUS PHASE

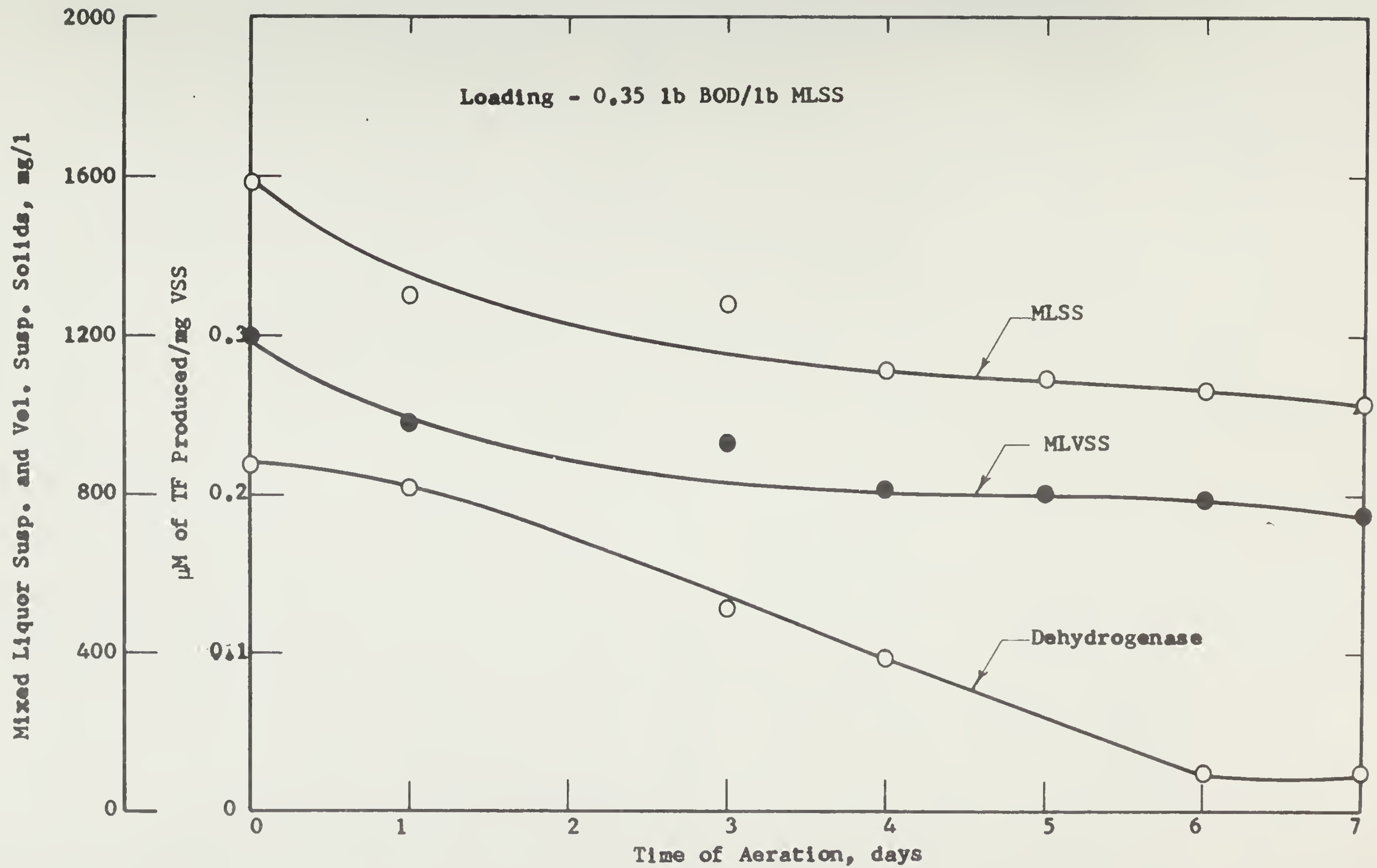


FIGURE 5.13 CHANGES IN SOLIDS AND ENZYME ACTIVITY IN ENDOGENOUS PHASE

However, there was still a considerable amount of solids left at the end of aeration. This can be explained as inert or unoxidizable solids accumulation. However, the sludge activity as measured by the dehydrogenase enzymes decreased considerably as can be seen in the figures.

Figures 5.14 and 5.16 show the changes in physical properties of sludge with time of aeration. Both yield strength and plastic viscosity decreased with time of aeration in the same manner as the synthesized biomass. The change in yield strength values was more noticeable than changes in plastic viscosity. The decrease in these values could be due to the effect of both decrease in concentration and biological activity. However, no definite pattern was found in these changes in physical properties, but it was only noticed that changes in biological characteristics of sludge were reflected in their physical properties.

5.4 Changes in Physical Properties of Activated Sludge during Initial Contact Period

The purpose of this study was to determine how physical parameters like viscosity and yield strength behave during the initial uptake stage of the organic substrate. During the initial uptake stage the organic material is quickly adsorbed by the microorganisms and also there is rapid storage of waste material into the body of the cells. This study was conducted in a batch system. A certain volume of sewage was added to acclimated sludge and COD, solids and physical properties were measured from the beginning of the experiment. The results of the experiment are summarized in Table 5.4. The curves obtained from viscometer data along with the equations of the curves as obtained by the method of least squares are shown in Figures 5.17, 5.18, 5.19, 5.20, and 5.21. The removal of COD and the growth of organisms as

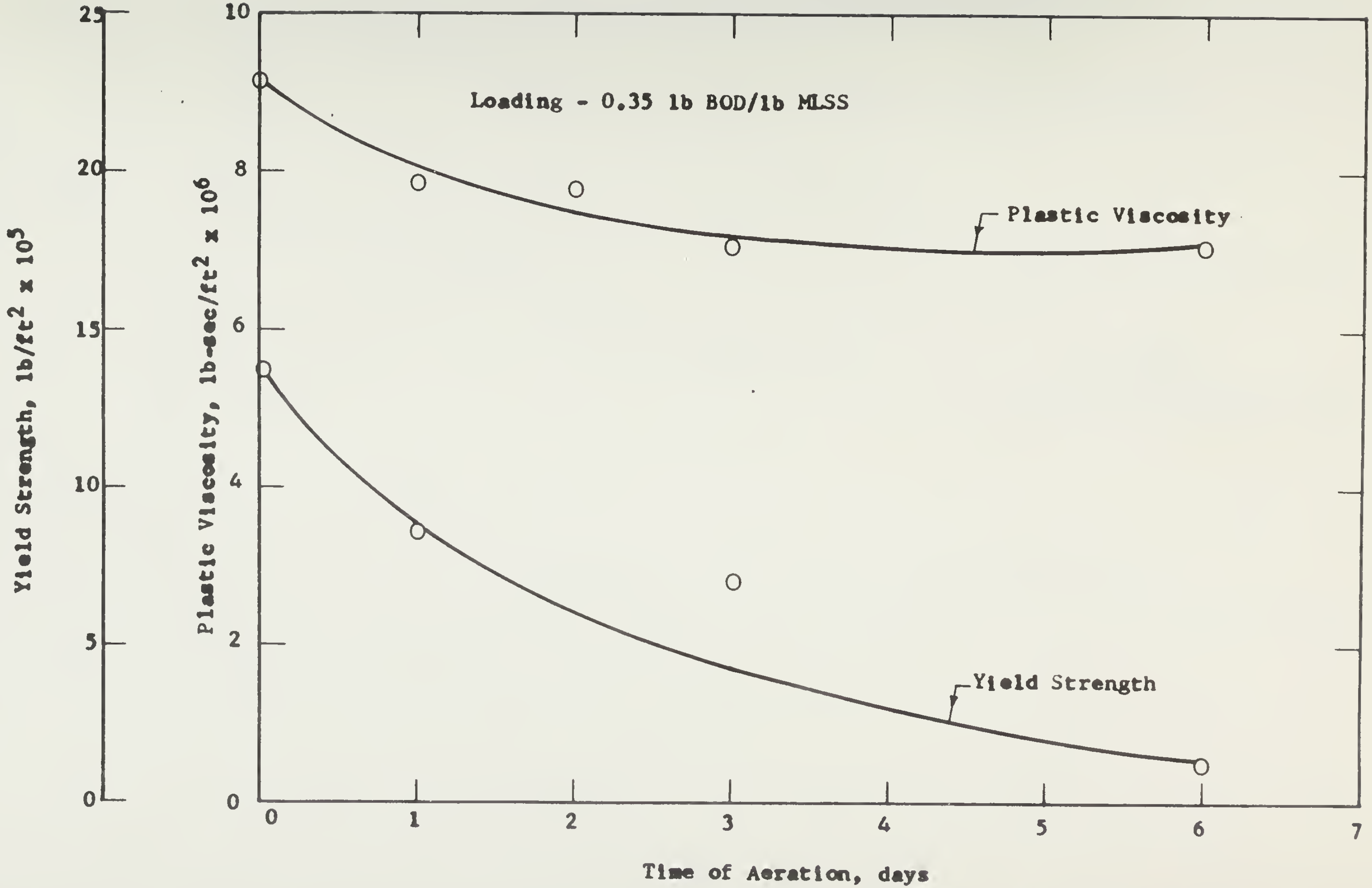


FIGURE 5.14 CHANGES IN PHYSICAL PROPERTIES IN ENDOGENOUS PHASE

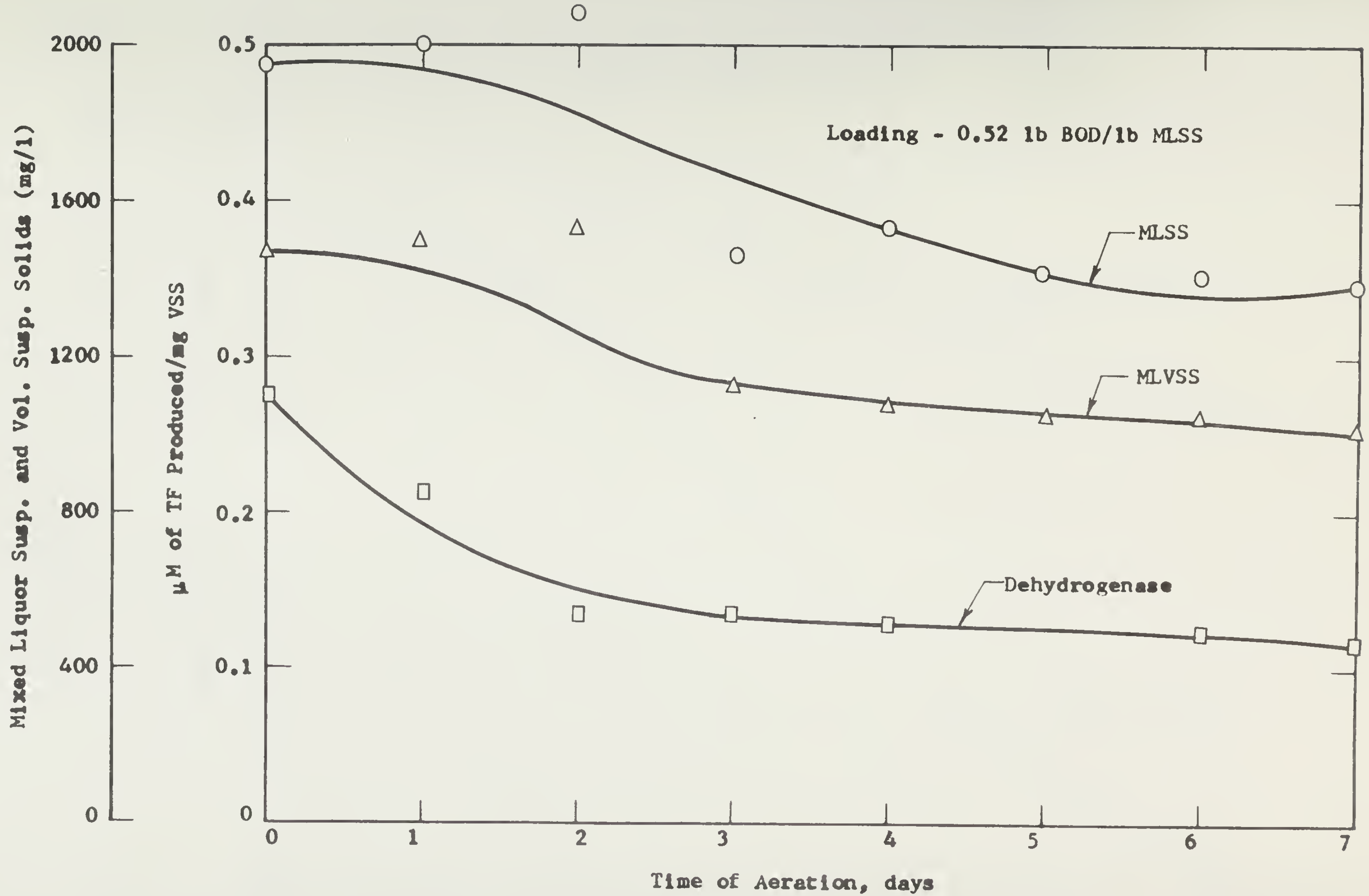


FIGURE 5.15 CHANGES IN SOLIDS AND ENZYME ACTIVITY IN ENDOGENOUS PHASE

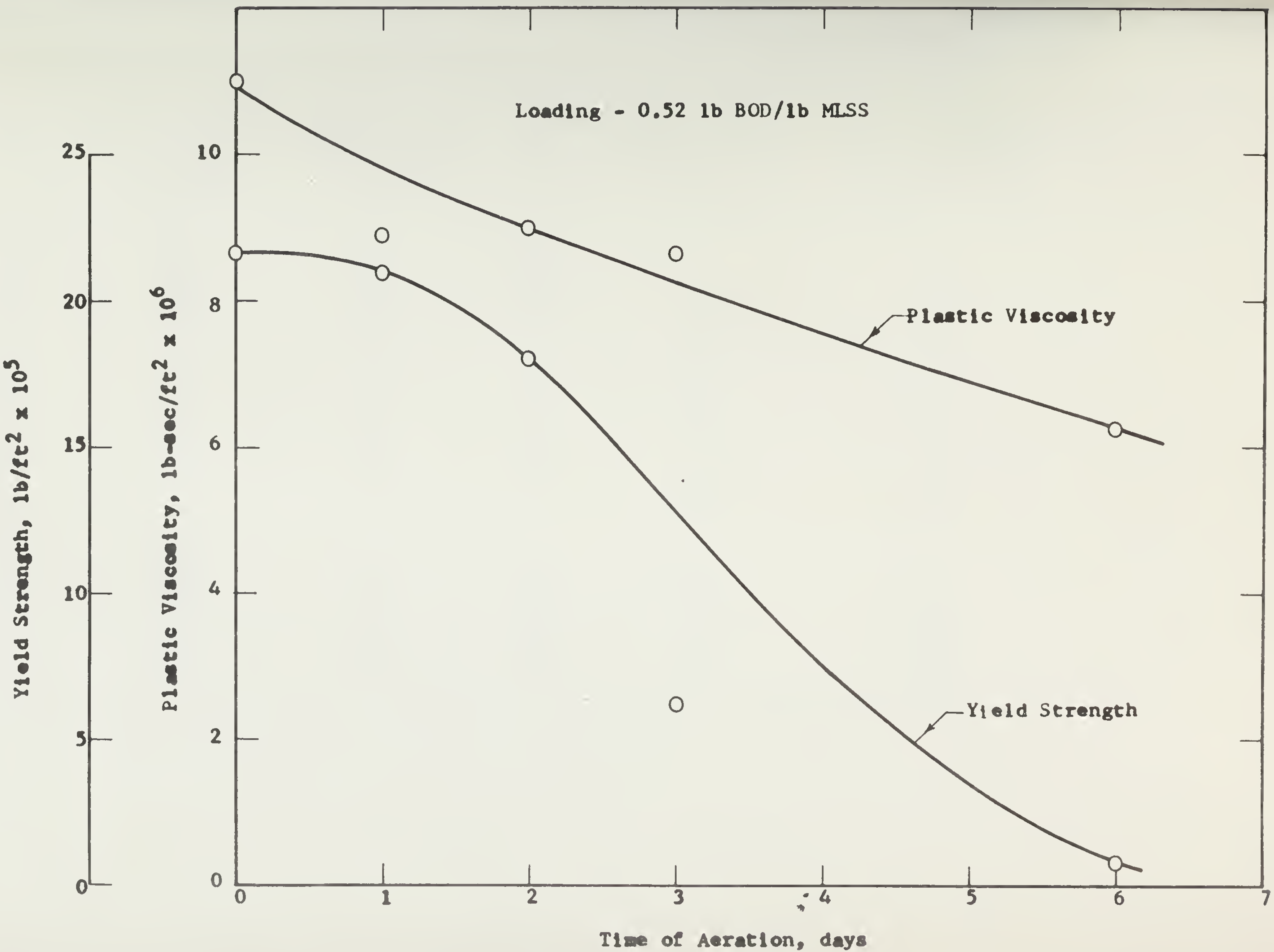


FIGURE 5.16 CHANGES IN PHYSICAL PROPERTIES IN ENDOGENOUS PHASE

Time (hr, min)	Total Susp. Solids (mg/ℓ)	Total Volatile Susp. Solids (mg/ℓ)	COD (mg/ℓ)	Yield Strength $(lb/ft^2) \times 10^5$	Plastic Viscosity $(lb\text{-}sec/ft^2) \times 10^6$
0, 0 min	1340	1000	3640	0	5.82
1	1510	1010	3240	--	--
3	1620	1220	3080	--	8.84
5	1650	1240	--	2.12	6.8
9	--	--	--	5.0	6.11
10	1655	1280	3160	--	--
16	--	--	--	10.0	5.54
20	1655	1280	3380	--	--
25	--	--	--	2.22	5.82
30	1630	1270	3240	--	--
32	--	--	--	1.39	5.63
45	--	--	--	5.3	6.5
1 hr	1615	--	--	2.5	6.6
2	1495	1150	3320	4.4	5.8
6	1495	1120	3280	2.78	6.30
9	1480	1110	3040	2.5	6.50
20	1380	1030	2800	1.11	6.21
24	1300	--	2600	0	6.01

Table 5.4 SUMMARY OF CHANGES DURING INITIAL CONTACT PERIOD

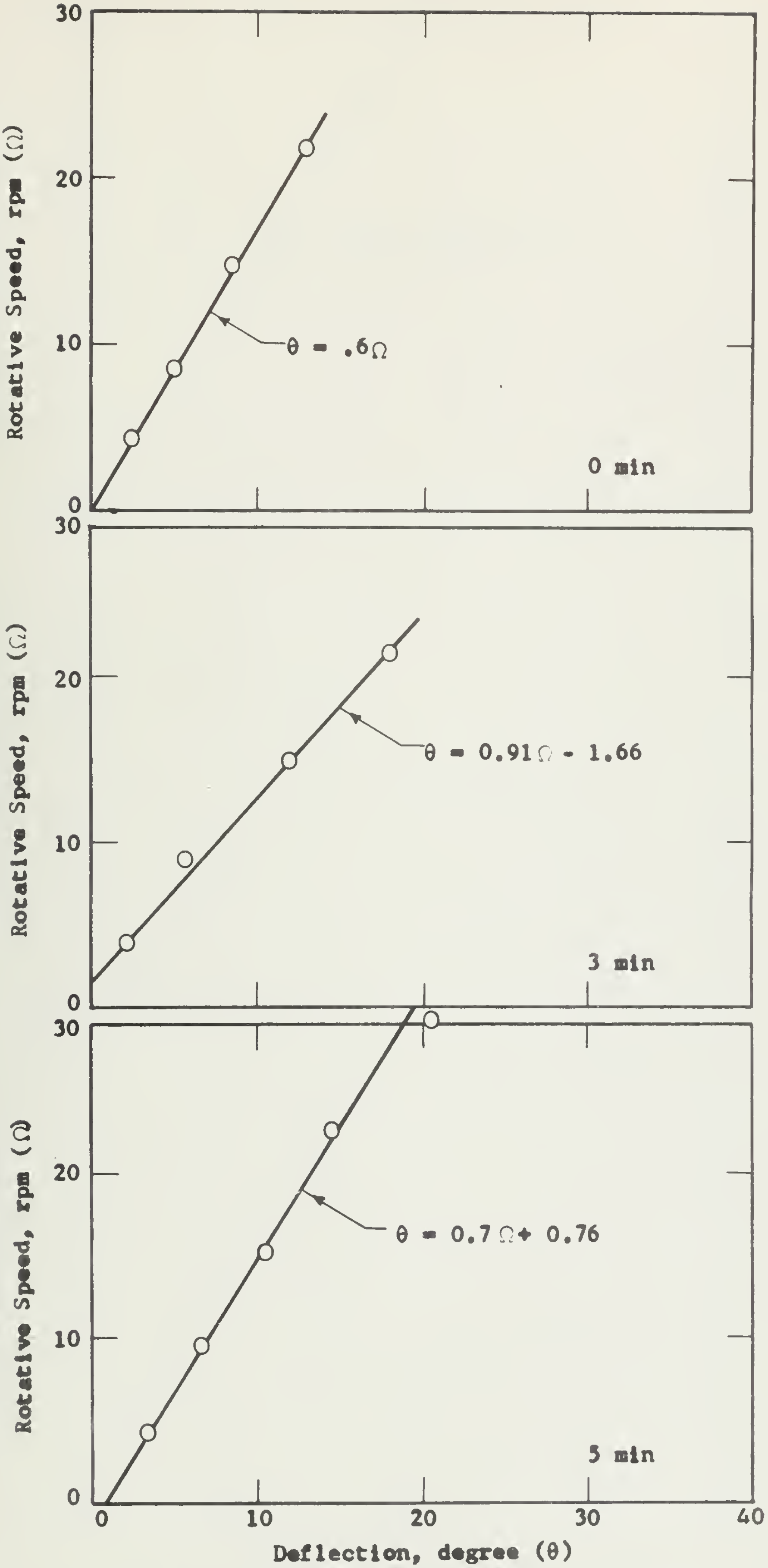


FIGURE 5.17 DETERMINATION OF PHYSICAL PROPERTIES IN INITIAL CONTACT PERIOD

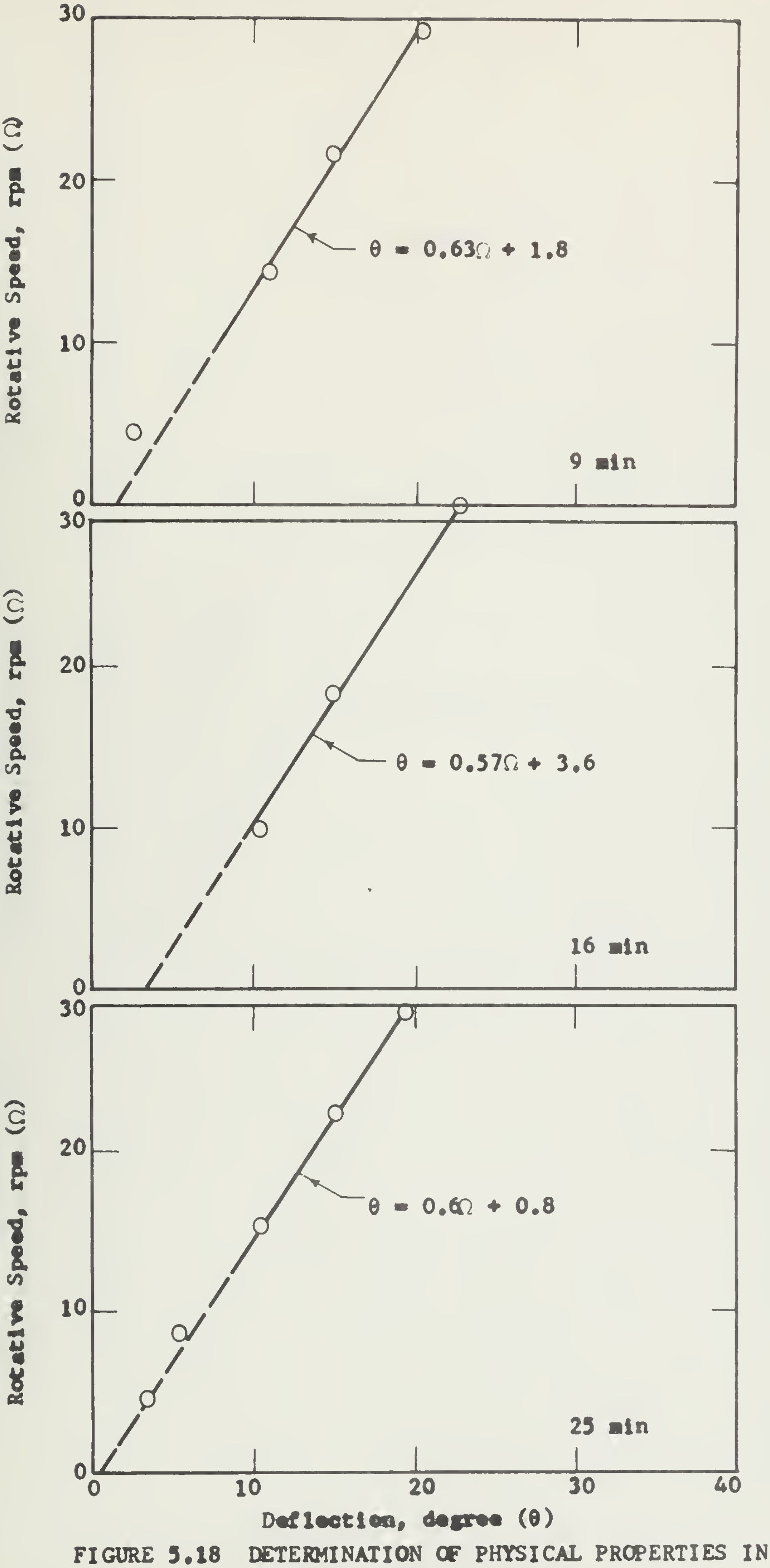


FIGURE 5.18 DETERMINATION OF PHYSICAL PROPERTIES IN INITIAL CONTACT PERIOD

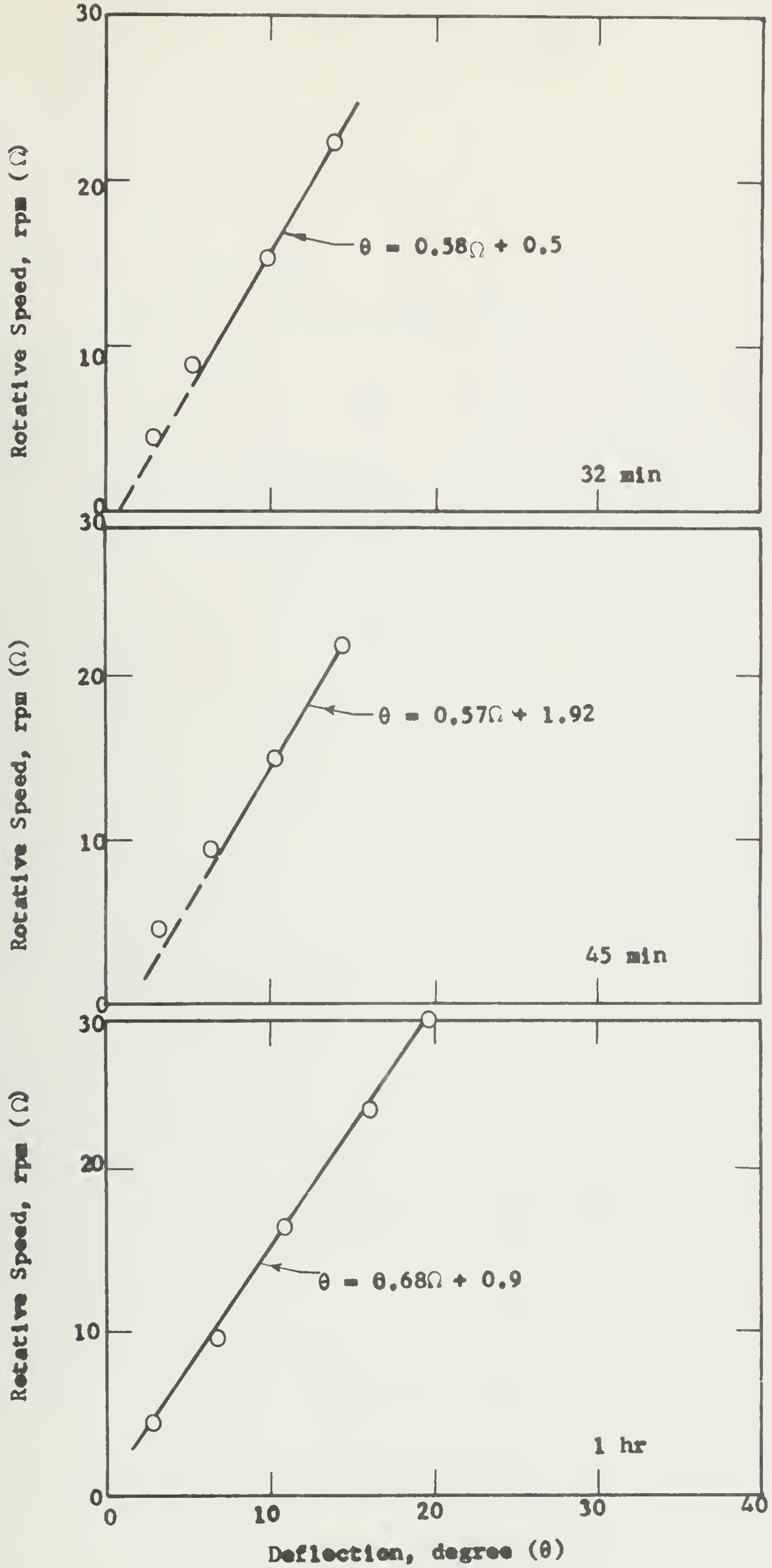


FIGURE 5.19 DETERMINATION OF PHYSICAL PROPERTIES IN INITIAL CONTACT PERIOD

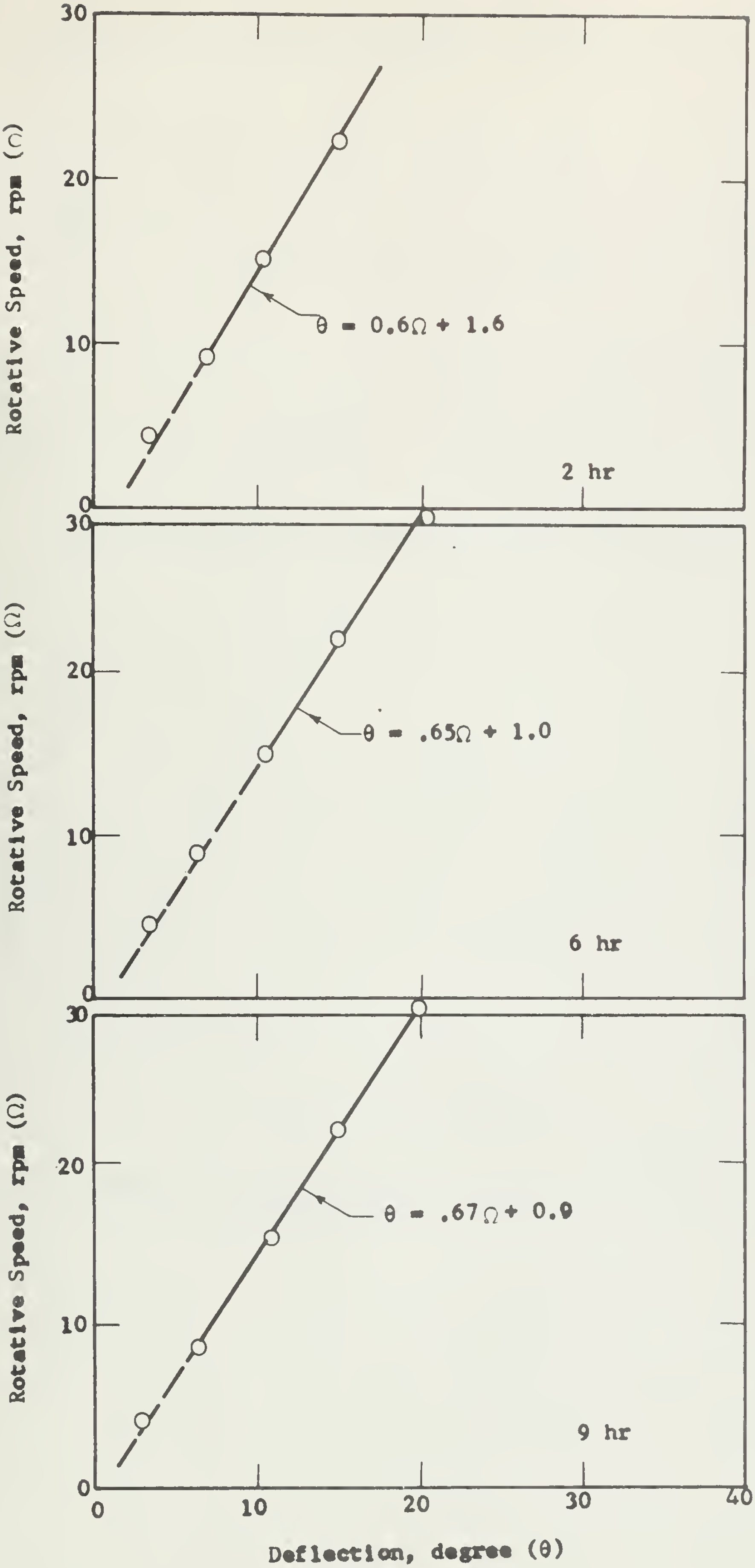


FIGURE 5.20 DETERMINATION OF PHYSICAL PROPERTIES IN INITIAL CONTACT PERIOD

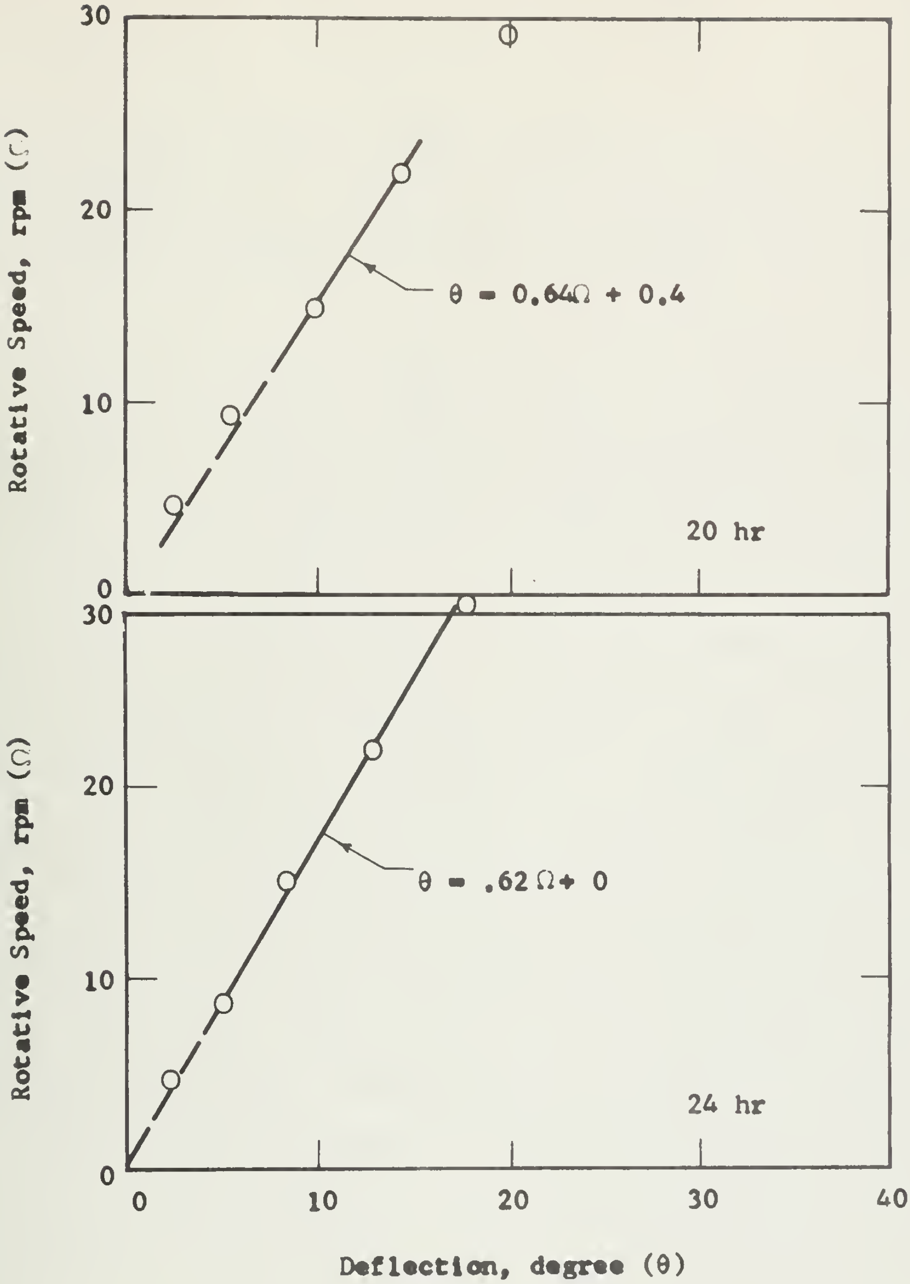


FIGURE 5.21 DETERMINATION OF PHYSICAL PROPERTIES IN INITIAL CONTACT PERIOD

determined by total suspended solids are given in Figure 5.22. Although the study was intended for observing changes in the parameters during initial removal stage, the measurements were taken throughout 24-hr periods of the day.

It can be seen from Figure 5.22 that the COD removal did not follow a definite pattern. There was no appreciable decrease in COD values during several hours. The COD values were determined on unfiltered mixed liquor. So it can be seen that during the initial uptake of COD by the organisms, the organic matter was stored in the body of the cells and the COD values of the mixed liquor did not change appreciably. However, during the rest of the experiment, decrease in COD values was not appreciable except during the long process of aeration when the solids started decreasing. The suspended solids attained the maximum concentration within one half hour of the start of the experiment. As it can be expected that due to high organic loading during the rapid uptake stage both the physical parameters, plastic viscosity, and yield strength, responded with high values as given in Figure 5.23. Plastic viscosity appeared to have a maximum value within the first 3 min of the experiment whereas the peak value of yield strength appeared in about 10 min. Yield strength values showed more fluctuations than the plastic viscosity values. However, the experiment was qualitative and no definite conclusion can be made. Since the system consisted of a heterogeneous population due to feeding of raw sewage instead of pure organic substrates, the results showed wide fluctuations in all the values.

However, it can be concluded from these studies that physical parameters do detect the changes in biological conditions in activated sludge, but to arrive at definite quantitative relationships for control of treatment plant operations more detailed studies would have to be conducted.

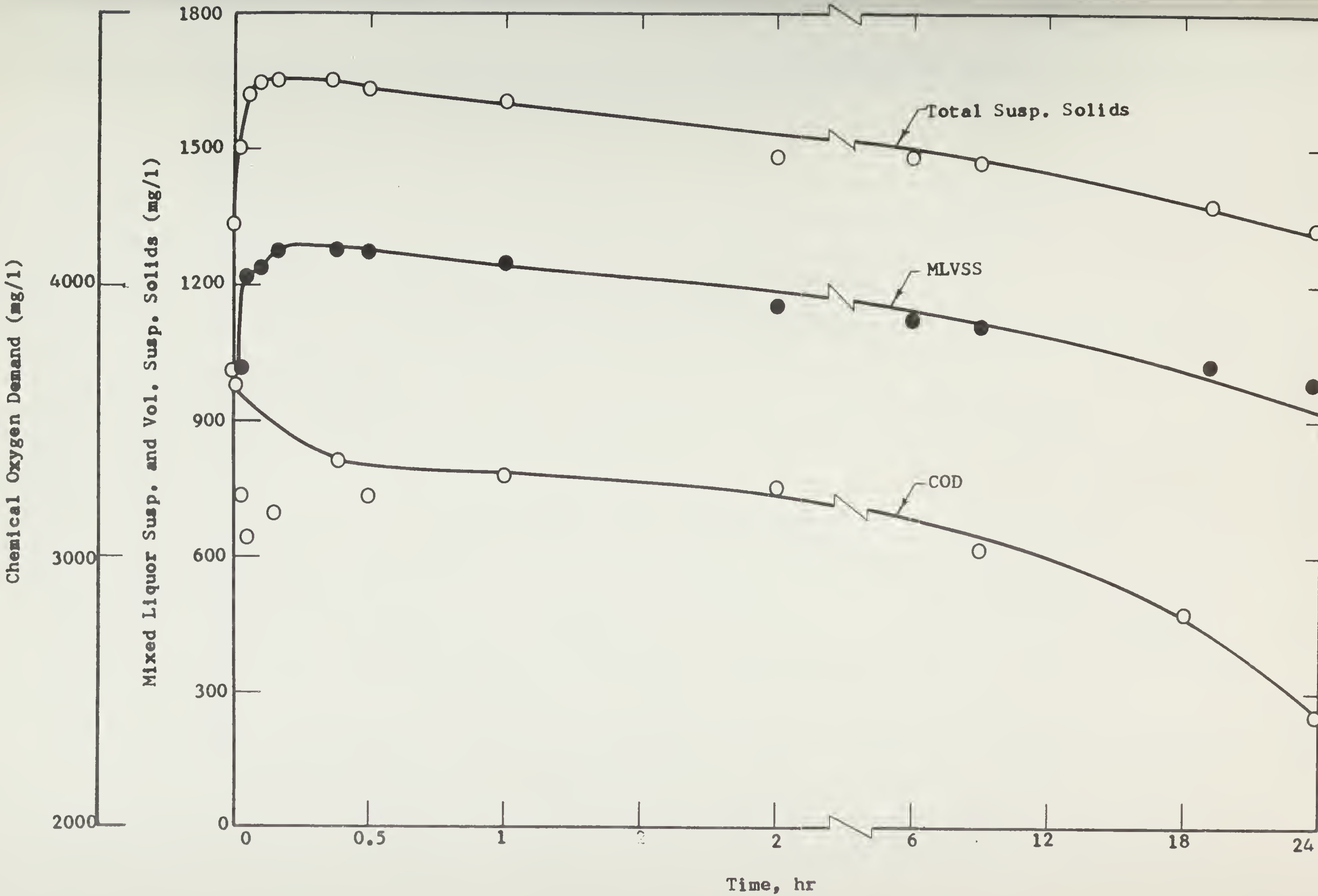


FIGURE 5.22 CHANGES IN SOLIDS AND COD DURING INITIAL CONTACT PERIOD

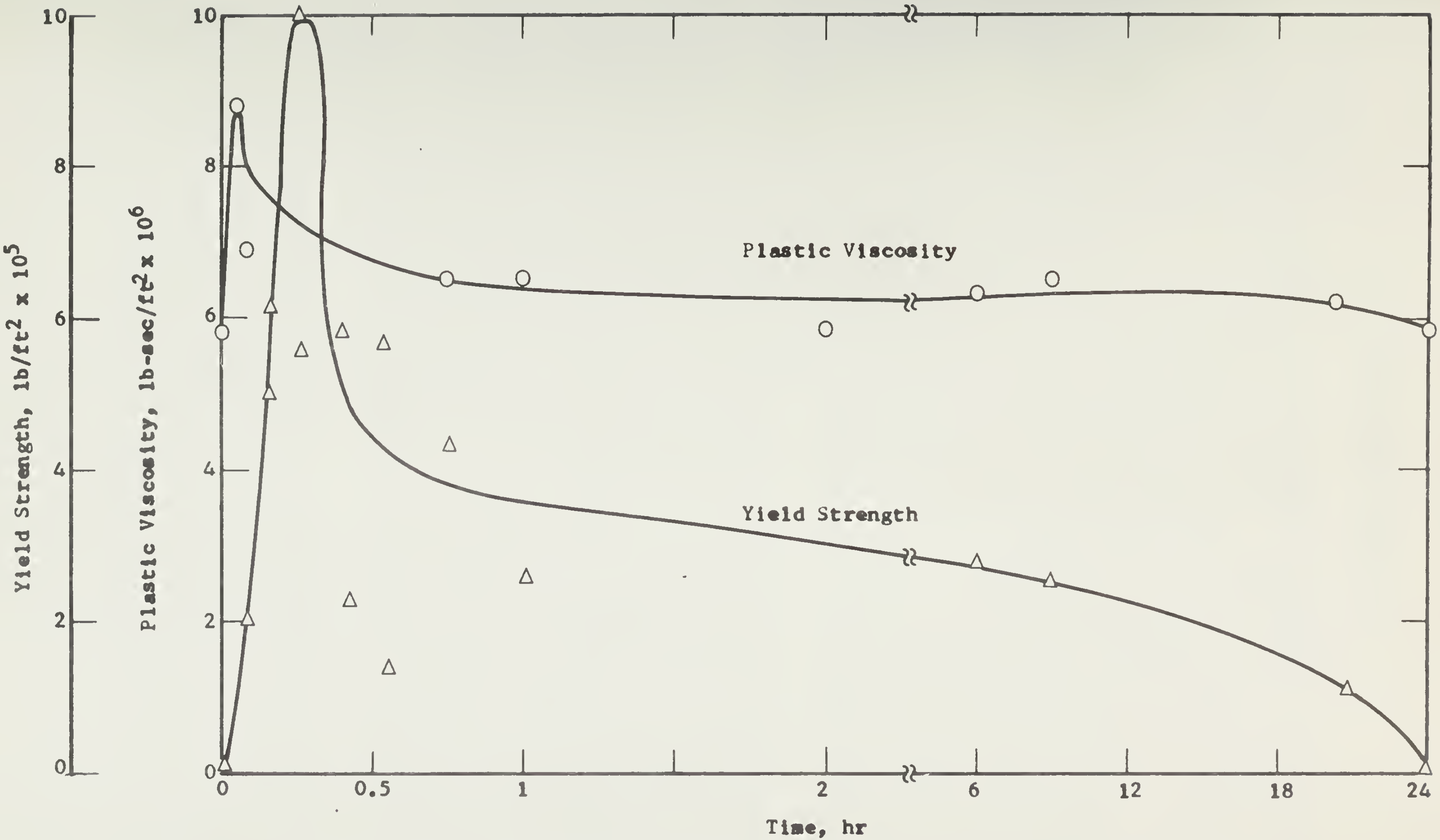


FIGURE 5.23 CHANGES IN PHYSICAL PROPERTIES DUEING INITIAL CONTACT PERIOD

6. SUMMARY AND CONCLUSIONS

It has been shown that the physical properties like viscosity and yield strength record changes in activated sludge due to a different biological condition. Yield strength is found to be dependent on both the concentration and the biological condition of a sludge.

It is expected that yield strength could be sensitive enough to be used in controlling the operation of biological treatment facilities, but it would be necessary to evaluate every sludge separately depending on the nature of the organic waste coming to the treatment plant. This study was undertaken to show that physical parameters as measured by the viscometer do detect changes in sludge quality as has been shown under different biological conditions.

Studies conducted on different phases of the treatment processes like initial contact period, or extended aeration showed that there was corresponding change in physical parameters and could be recorded by a suitable viscometer. Although no quantitative relationships were obtained, it was felt that with properly designed pilot plant studies, more quantitative and useful relationships may be obtained.

Studies on dehydrogenase enzyme activity showed that dehydrogenase enzymes as measured by TTC responded significantly with changes in organic loading.

The unfiltered sewage from a primary settling tank was used as a feed in this study. More detailed study was not possible with this type of organic feed. However, with synthetic organic feed the load spectrum can be extended and the parameters can be measured under more controlled conditions.

This study can also be extended to measure the changes in the physical properties of the sludge due to nitrogen deficiency, shock load, toxic materials, etc.

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